# SUSY and the LHC: She was not around the corner
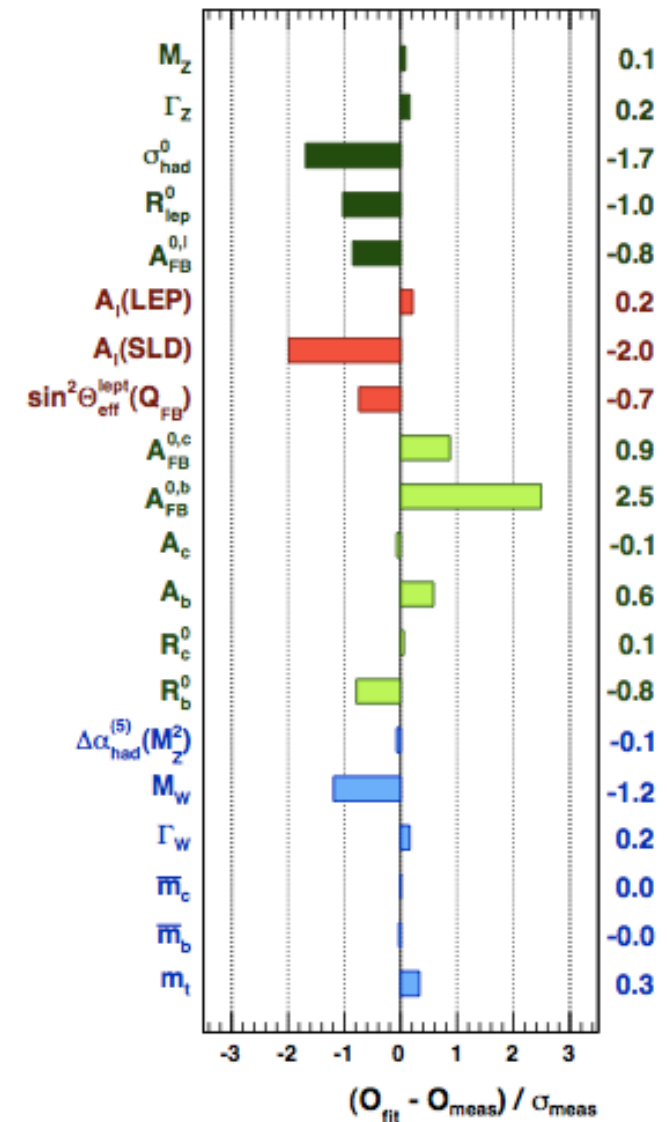
Iacopo Vivarelli
Albert-Ludwigs Universität - Freiburg
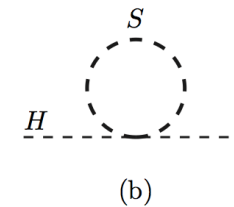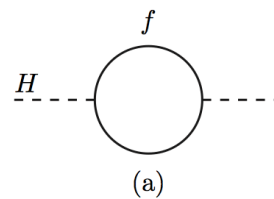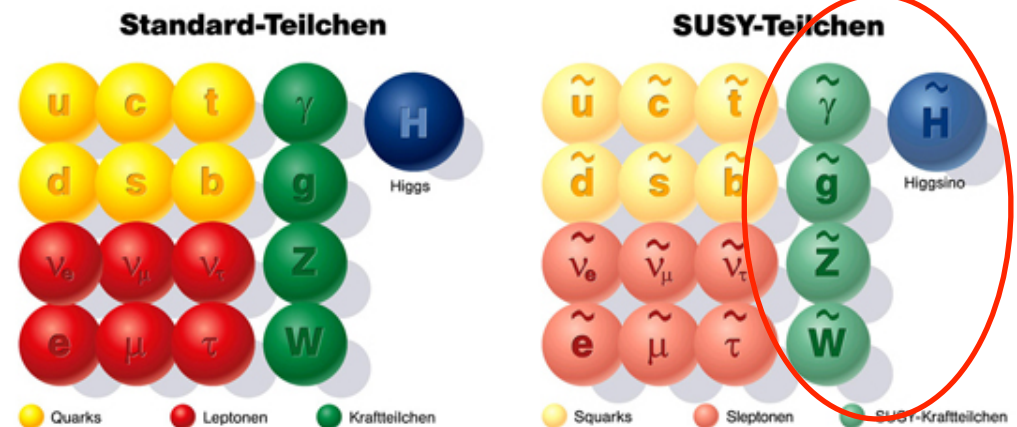
# Extend the Standard Model?

- The Standard Model is working fine. Why fix it?

  - a) The Higgs sector suffers from quadratically divergent loop corrections (high level of fine-tuning)

  - b) Cosmological data call for a dark matter candidate: no such candidate is present in the SM

  - c) Moreover, no further unification between the EW and QCD possible, no explanation for EW symmetry breaking, no easy way to include gravity, etc.

- *Supersymmetry (SUSY) offers an elegant solution for a), which can simultaneously address b) and c)*

| | $(O_{fit} - O_{meas}) / \sigma_{meas}$ | |
|---|---|---|
| $M_Z$ | | 0.1 |
| $\Gamma_Z$ | | 0.2 |
| $\sigma^0_{had}$ | | -1.7 |
| $R^0_{lep}$ | | -1.0 |
| $A^{0,l}_{FB}$ | | -0.8 |
| $A_l(LEP)$ | | 0.2 |
| $A_l(SLD)$ | | -2.0 |
| $\sin^2\Theta^{lept}_{eff}(Q_{FB})$ | | -0.7 |
| $A^{0,c}_{FB}$ | | 0.9 |
| $A^{0,b}_{FB}$ | | 2.5 |
| $A_c$ | | -0.1 |
| $A_b$ | | 0.6 |
| $R^0_c$ | | 0.1 |
| $R^0_b$ | | -0.8 |
| $\Delta\alpha^{(5)}_{had}(M^2_Z)$ | | -0.1 |
| $M_W$ | | -1.2 |
| $\Gamma_W$ | | 0.2 |
| $\overline{m}_c$ | | 0.0 |
| $\overline{m}_b$ | | -0.0 |
| $m_t$ | | 0.3 |

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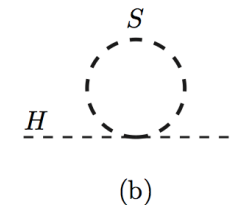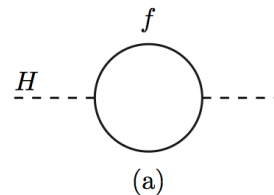
# Supersymmetry (SUSY)

- SUSY is **a symmetry that relates bosons and fermions**

- In the Minimal Supersymmetric Extension of the Standard Model (MSSM):

  - a new set of fields differing in spin by 1/2 w.r.t. the SM partners (hierarchy problem solved "naturally")



Mix into neutralinos and charginos

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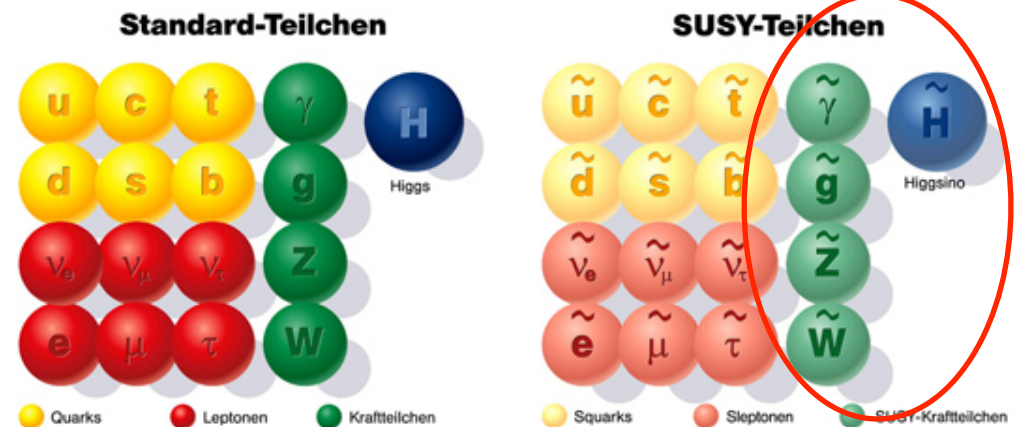
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**Standard-Teilchen**

**SUSY-Teilchen**

Mix into neutralinos and charginos

$$W \ni \frac{1}{2}\lambda_{ijk}L_i L_j E_k^c + \lambda'_{ijk}L_i Q_j D_k^c + \frac{1}{2}\lambda''_{ijk}U_i^c D_j^c D_k^c + \mu_i L_i H_u$$

- Lepton and baryon number violation allowed → proton decay

- If R-parity conservation assumed, the **Lightest Supersymmetric Particle (LSP)** is stable: natural Dark Matter candidate

R-parity = $(-1)^{3(B-L)+2s}$
-1 for sparticles
1 for particles

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# Why SUSY at the EW scale?

- If SUSY is realised at **some high energy scale** with no measurable effect at the EW scale, **why would we (experimentalist) care**?

- Generic arguments to <span style="color:orange">**expect SUSY to play a role at the EW scale**</span>:

  - **Low fine tuning if $M_{SUSY} \sim 1$ TeV** (therefore within current reach in terms of experiments at colliders)

  - **WIMP miracle of dark matter**:

    - Dark matter relic abundance and interaction cross section related one to the other

    - If cross section EW, then $M_{dark} \sim 0.1/1$ TeV



Mass of Dark Matter Particle from Supersymmetry (TeV)

Fraction of Total-Dark Matter Density
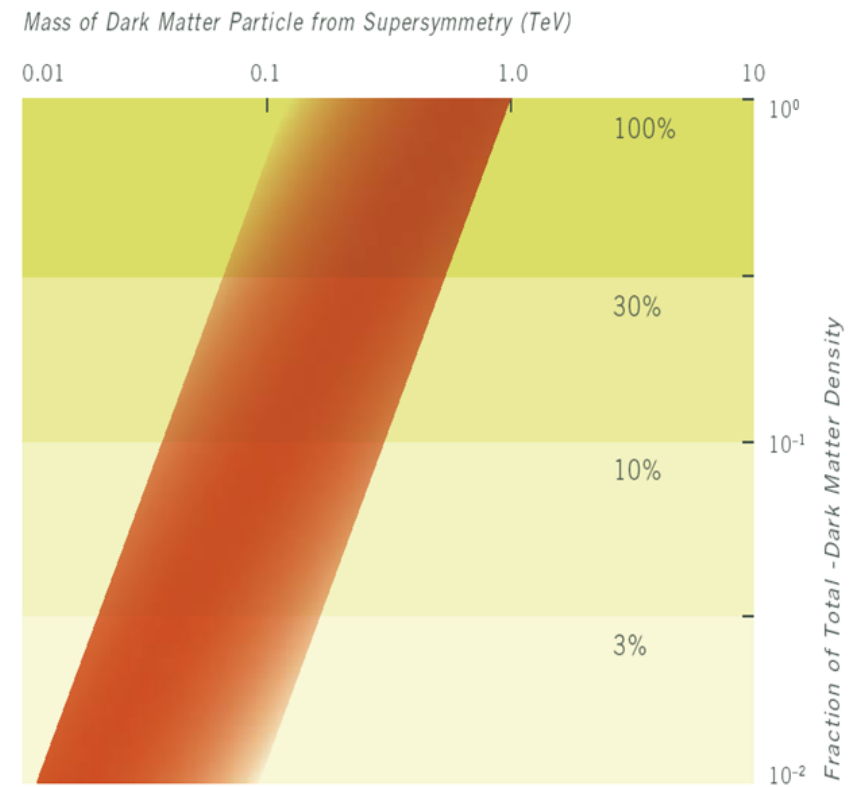
HEPAP 2006 LHC/ILC Subpanel

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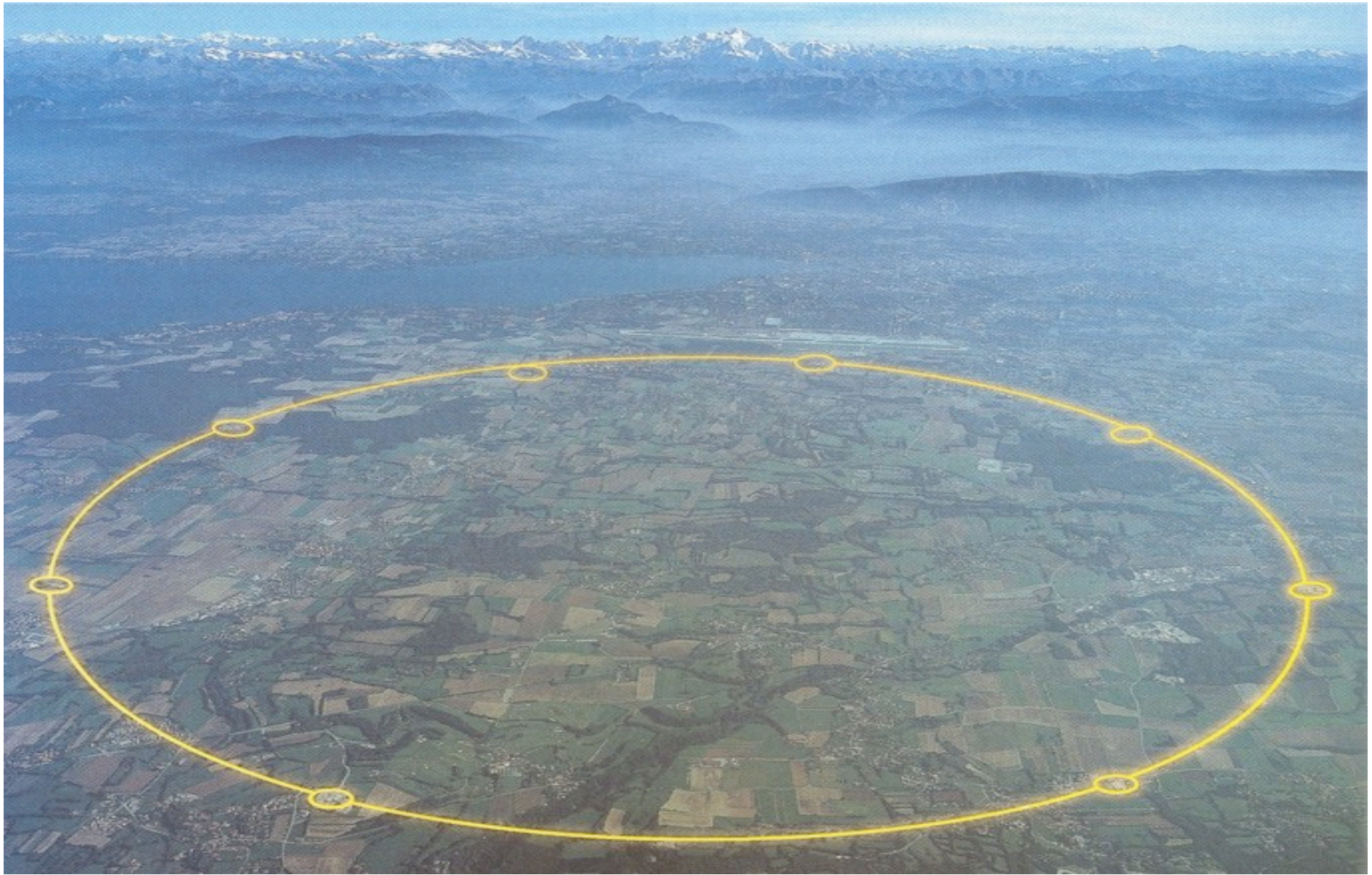
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# SUSY around the corner?

- The Large Hadron Collider has been built to:

  1. **Fully investigate the mechanism of the EW symmetry breaking**

  2. **Break the Standard Model:** find SUSY (or any other manifestation of physics beyond the standard model) at the TeV scale

- Early discovery of (EW) R-parity conserving SUSY surely possible by looking at excesses of events with large missing transverse momentum and high jet multiplicity
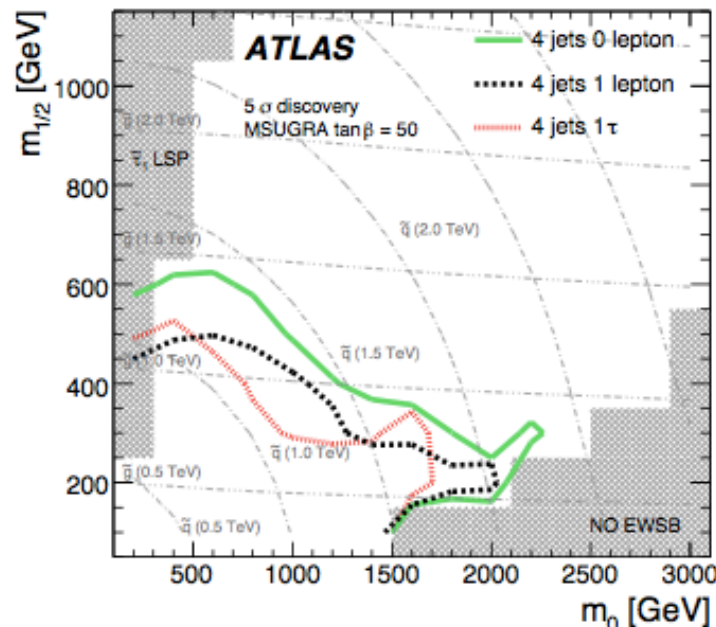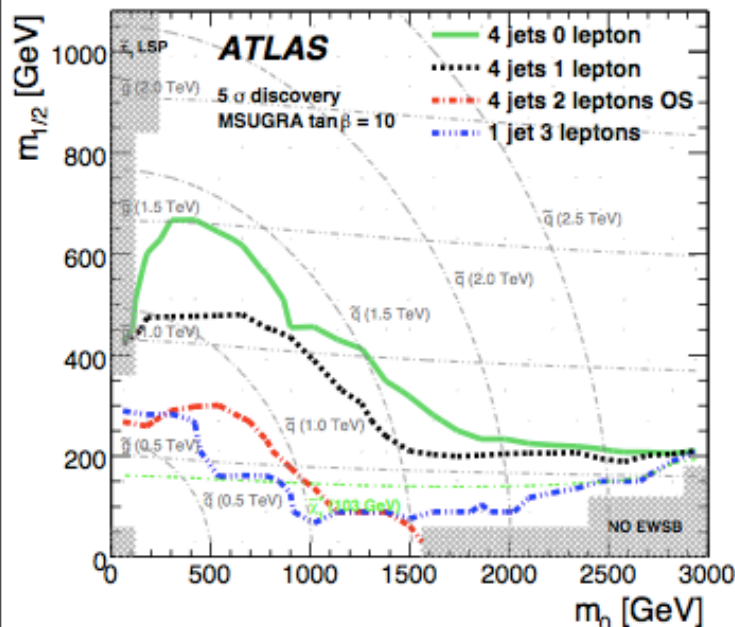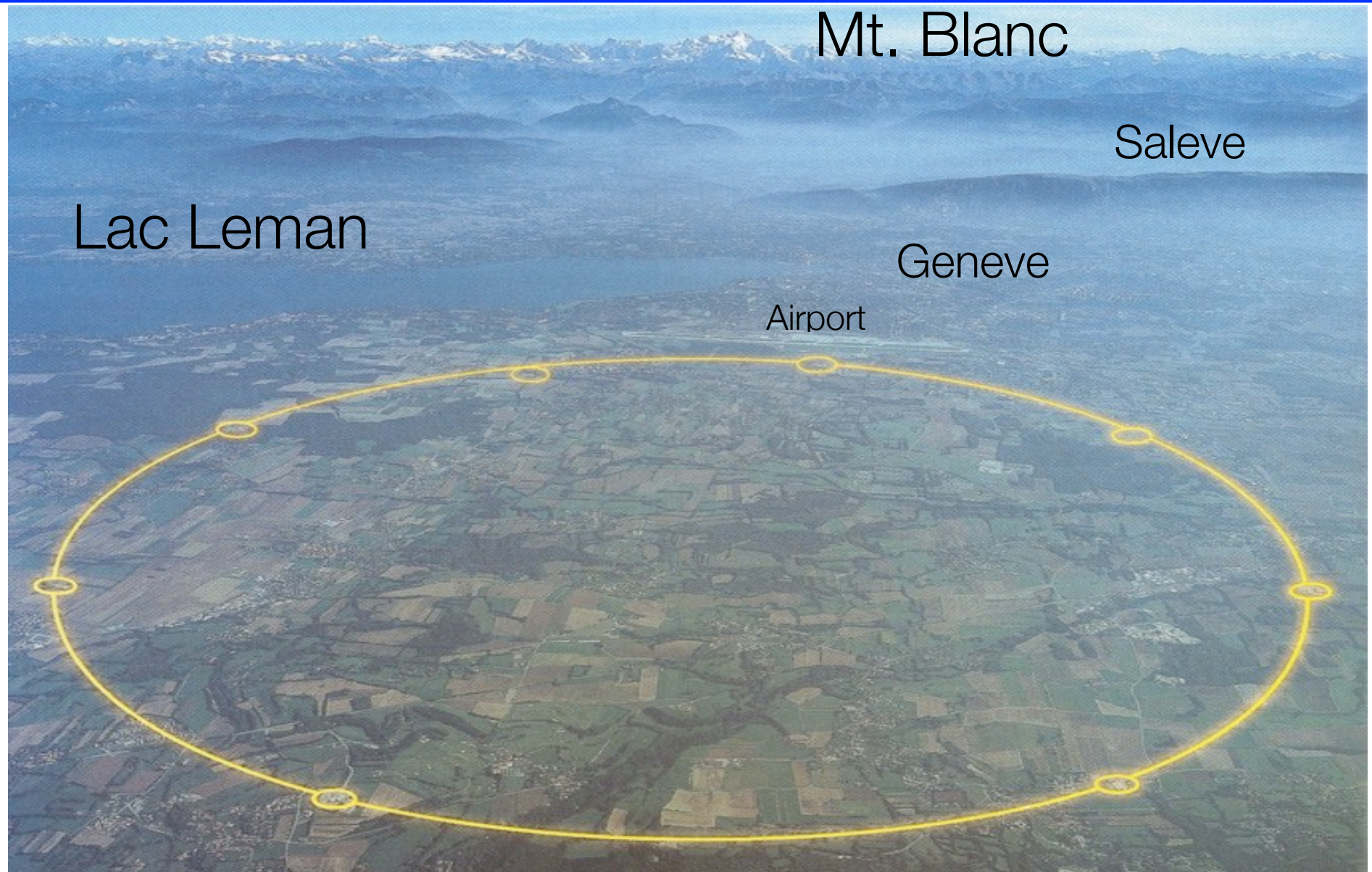
Prospect for mSUGRA/CMSSM discovery (1 fb$^{-1}$) before switching on LHC ($\sqrt{s}$=10 TeV)

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# Experimental setup

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# Experimental setup



Mt. Blanc

Saleve

Lac Leman

Geneve

Airport

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# Experimental setup

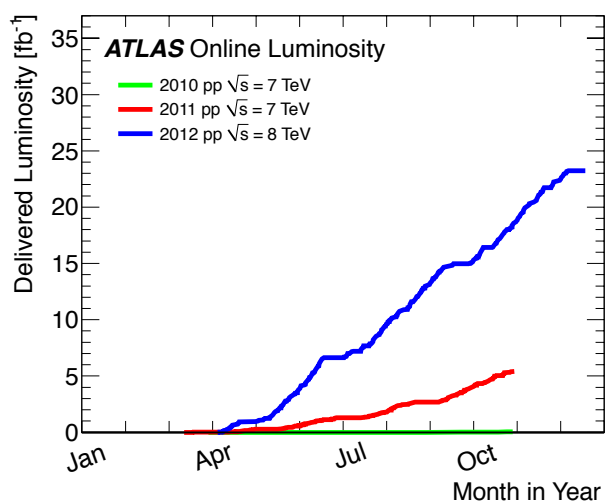SUSY and the LHC - 8th January 2013 - LBNL
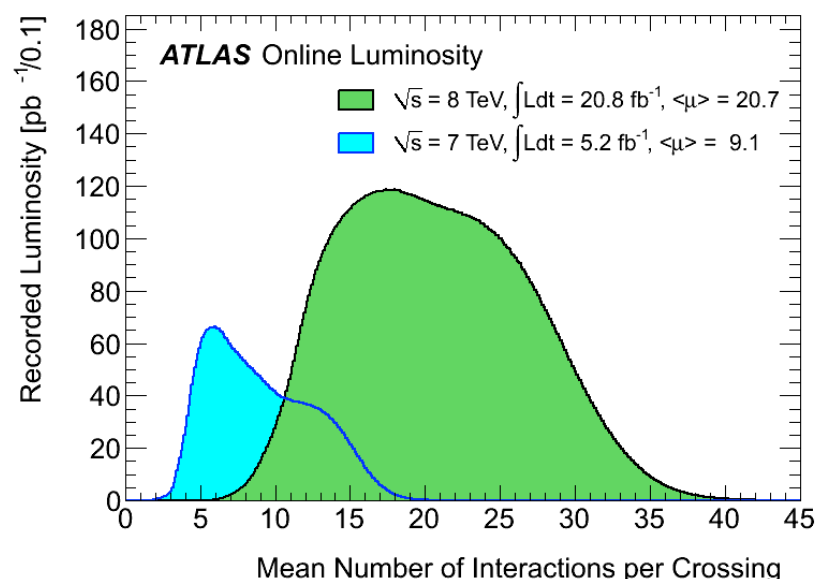
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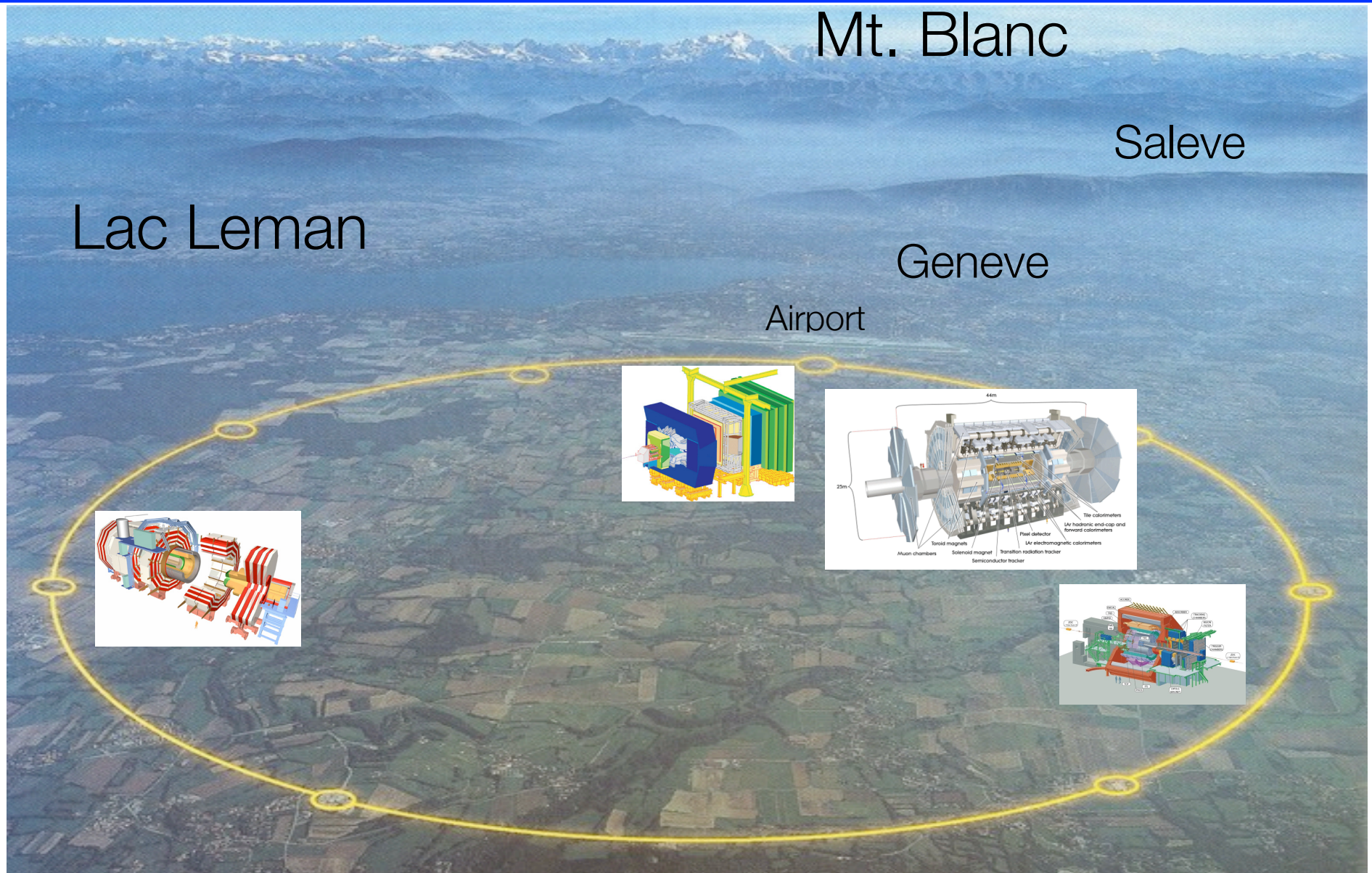
# LHC - performance of the machine

- About 22 fb$^{-1}$ collected at $\sqrt{s}$= 8 TeV and 5 fb$^{-1}$ at $\sqrt{s}$= 7 TeV (per experiment) in 2011
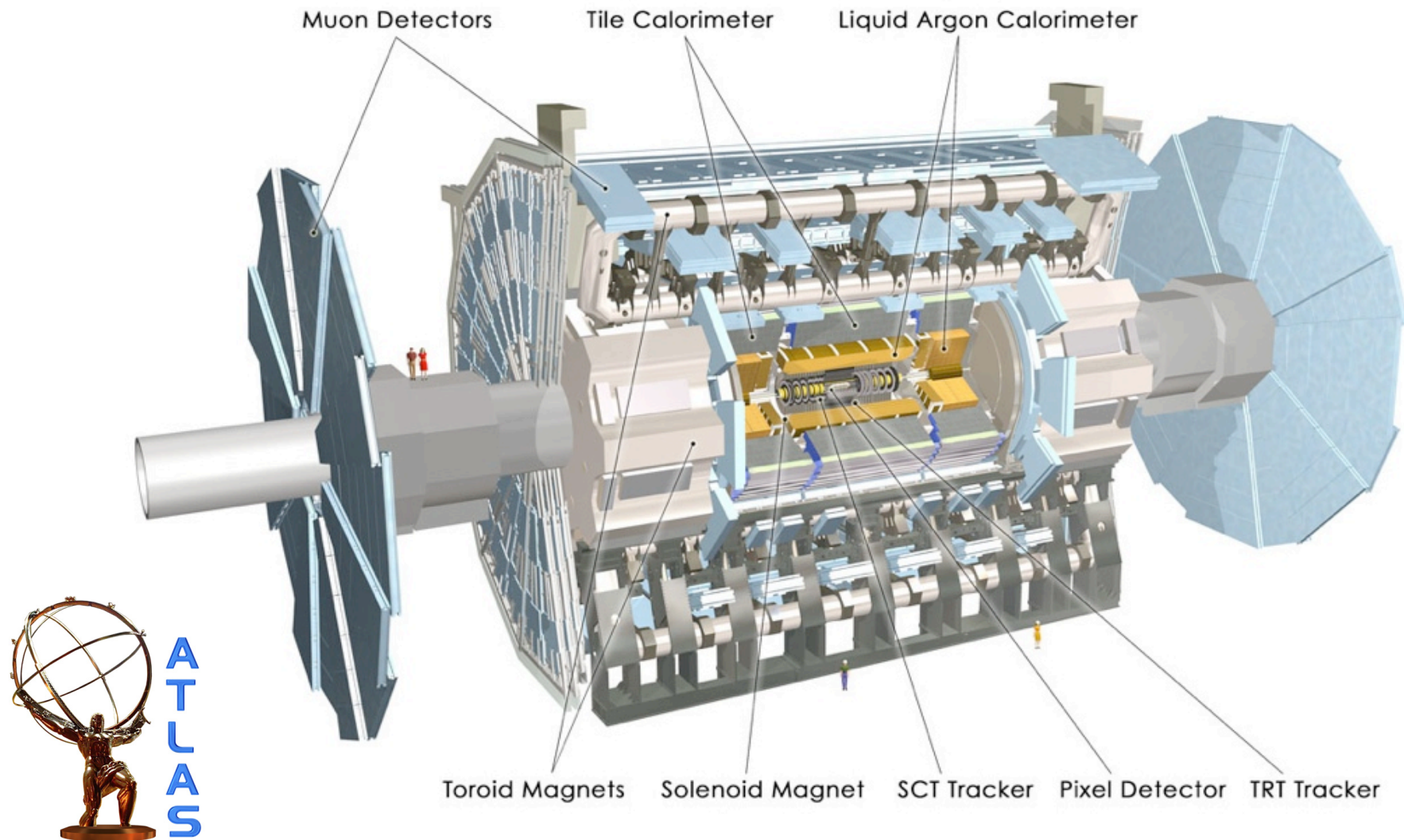  - Most of which with more than 95% of the detectors operational



| Subdetector | Number of Channels | Approximate Operational Fraction |
|---|---|---|
| Pixels | 80 M | 95.0% |
| SCT Silicon Strips | 6.3 M | 99.3% |
| TRT Transition Radiation Tracker | 350 k | 97.5% |
| LAr EM Calorimeter | 170 k | 99.9% |
| Tile calorimeter | 9800 | 98.3% |
| Hadronic endcap LAr calorimeter | 5600 | 99.6% |
| Forward LAr calorimeter | 3500 | 99.8% |
| LVL1 Calo trigger | 7160 | 100% |
| LVL1 Muon RPC trigger | 370 k | 100% |
| LVL1 Muon TGC trigger | 320 k | 100% |
| MDT Muon Drift Tubes | 350 k | 99.7% |
| CSC Cathode Strip Chambers | 31 k | 96.0% |
| RPC Barrel Muon Chambers | 370 k | 97.1% |
| TGC Endcap Muon Chambers | 320 k | 98.2% |

- Most of the analysis so far use 13 fb$^{-1}$. results being updated for the winter conferences

- **Large luminosity** means **large pileup** (higher than initially planned) . Careful pileup suppression strategies developed.

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# The detector

# What we are typically doing

- **Heavy sparticles produced** in the primary collision

- They **decay into lighter objects**, emitting (high) $P_T$ jets and possibly other objects (leptons, photons) and MET (LSP)

- A "typical" SUSY event will have **large MET and** **large $H_T$**



- Useful variables:

$$H_T = \sum_{jets} p_T^{jets} \left( + \sum_l p_T^l + ... \right)$$

$$M_{eff} = E_T^{miss} + H_T$$



- But also other variables with well defined kinematical end point for the SM background

  - **$M_T$ (lepton-MET):** end point at $M_W$ if produced in W decay

  - **$M_{T2}$, $M_{CT}$:** assume pair produced heavy particles with visible and invisible decays

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# Jet measurement

- **Constantly improving** on jet measurement and pileup suppression techniques

- **Jet energy scale** (isolated jets) known at the ~1% level

- thanks to the combination of **several in situ techniques** (gamma/Z+jet balance, di-jet and multi-jet balance, calorimeter/track response comparison)

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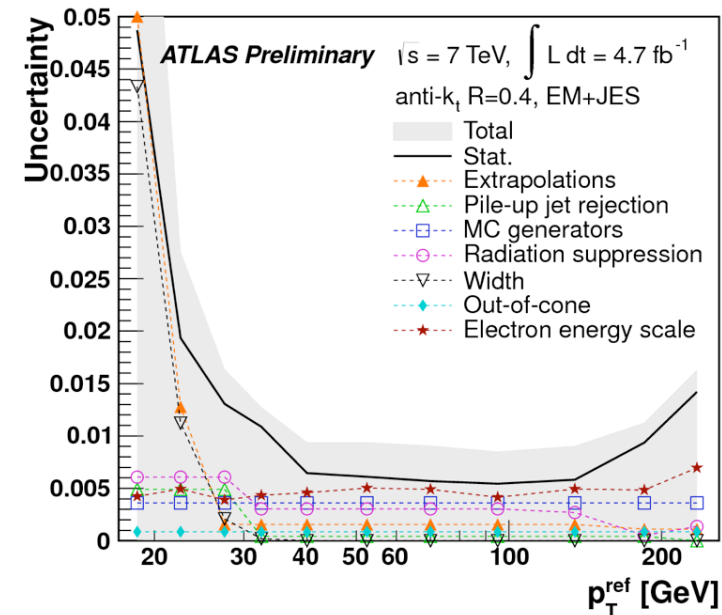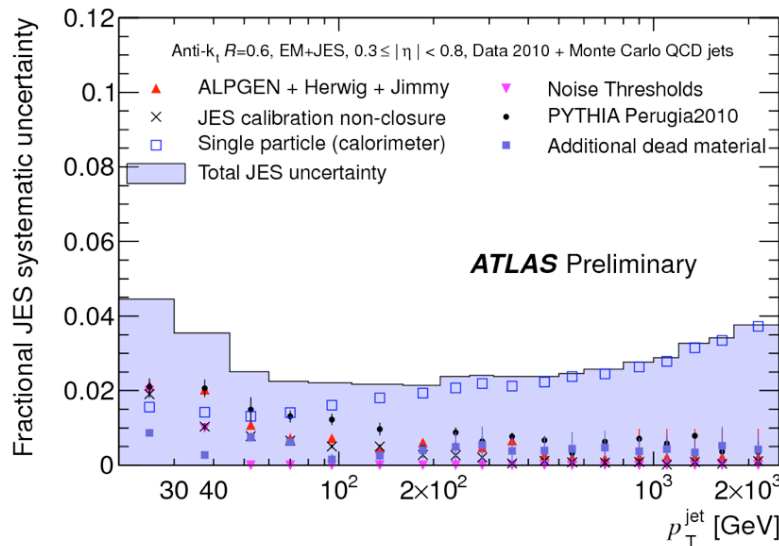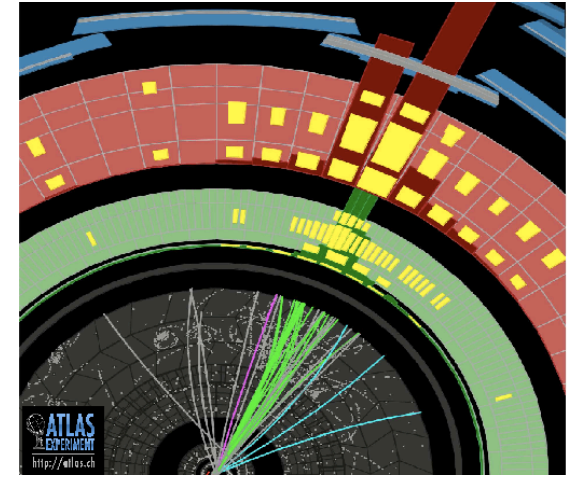
# Missing transverse energy and b-tagging

- Missing $E_T$ (MET) reconstructed from the vectorial sum of **all final state objects,** each **with a dedicated calibration.**

- Large sensitivity of **missing $E_T$ resolution to pileup** addressed by **usage of tracking information in MET calculation**
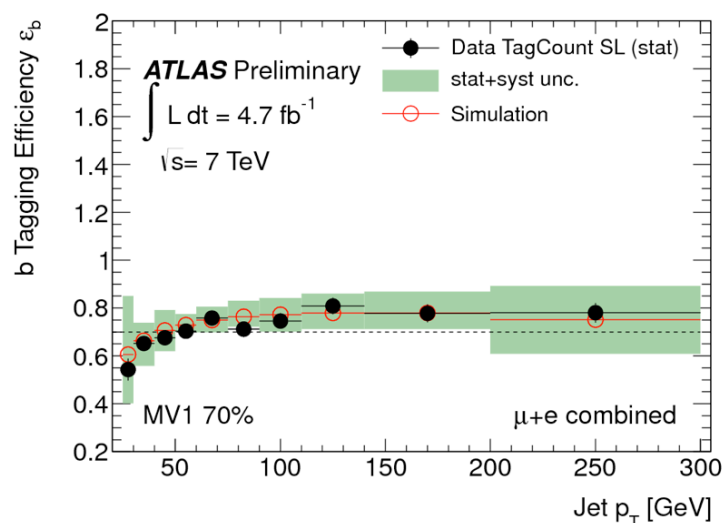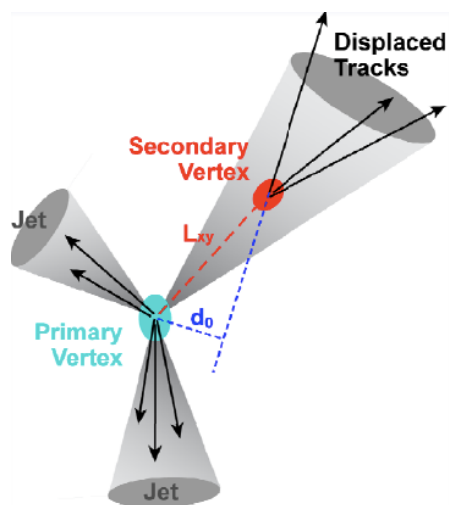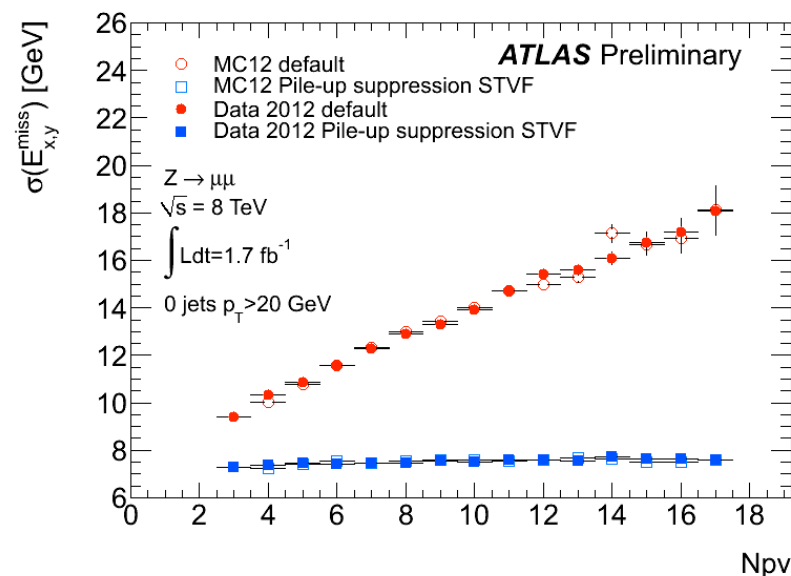


- **b-tagging:** neural network algorithm combining informations about **secondary vertex displacement** and **impact parameters of jets**

- efficiencies **generally well reproduced by MC**. Systematic uncertainties **of the order of 10-15%**

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# The Standard Model in one slide
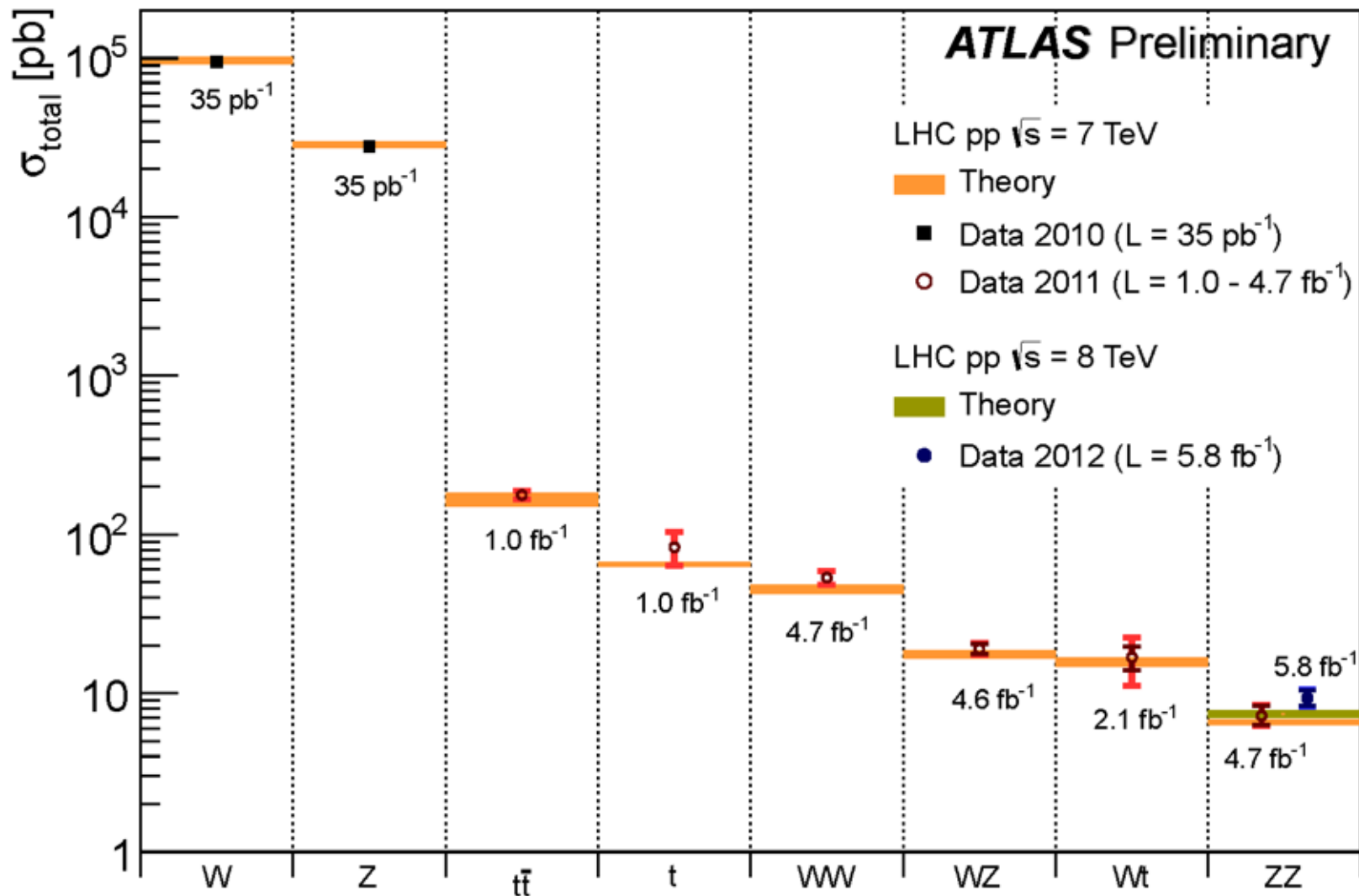
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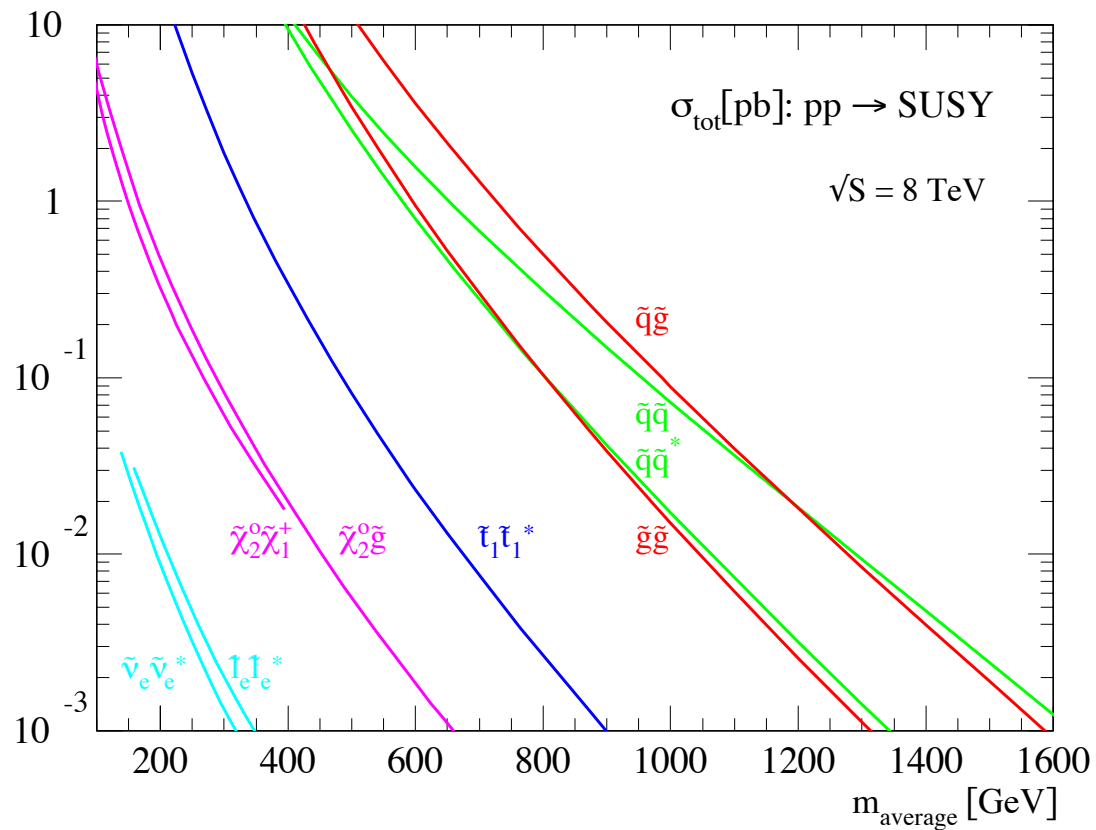
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# SUSY searches

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# What processes are we looking for?

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# What processes are we looking for?



$\sigma_{tot}[pb]$: pp → SUSY

$\sqrt{S}$ = 8 TeV

**Strong production**

$\tilde{q}\tilde{g}$

$\tilde{q}\tilde{q}$
$\tilde{q}\tilde{q}^*$

$\tilde{g}\tilde{g}$

$\tilde{\chi}_2^0\tilde{\chi}_1^+$    $\tilde{\chi}_2^0\tilde{g}$    $\tilde{t}_1\tilde{t}_1^*$

$\tilde{\nu}_e\tilde{\nu}_e^*$    $\tilde{l}_e\tilde{l}_e^*$

$m_{average}$ [GeV]

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$\sigma_{tot}$[pb]: pp → SUSY

$\sqrt{S}$ = 8 TeV

Electroweak production

$\tilde{q}\tilde{g}$

$\tilde{q}\tilde{q}$
$\tilde{q}\tilde{q}^*$

$\tilde{g}\tilde{g}$

$\tilde{\chi}_2^o\tilde{\chi}_1^+$   $\tilde{\chi}_2^o\tilde{g}$   $\tilde{t}_1\tilde{t}_1^*$

$\tilde{\nu}_e\tilde{\nu}_e^*$   $\tilde{l}_e\tilde{l}_e^*$

$m_{average}$ [GeV]
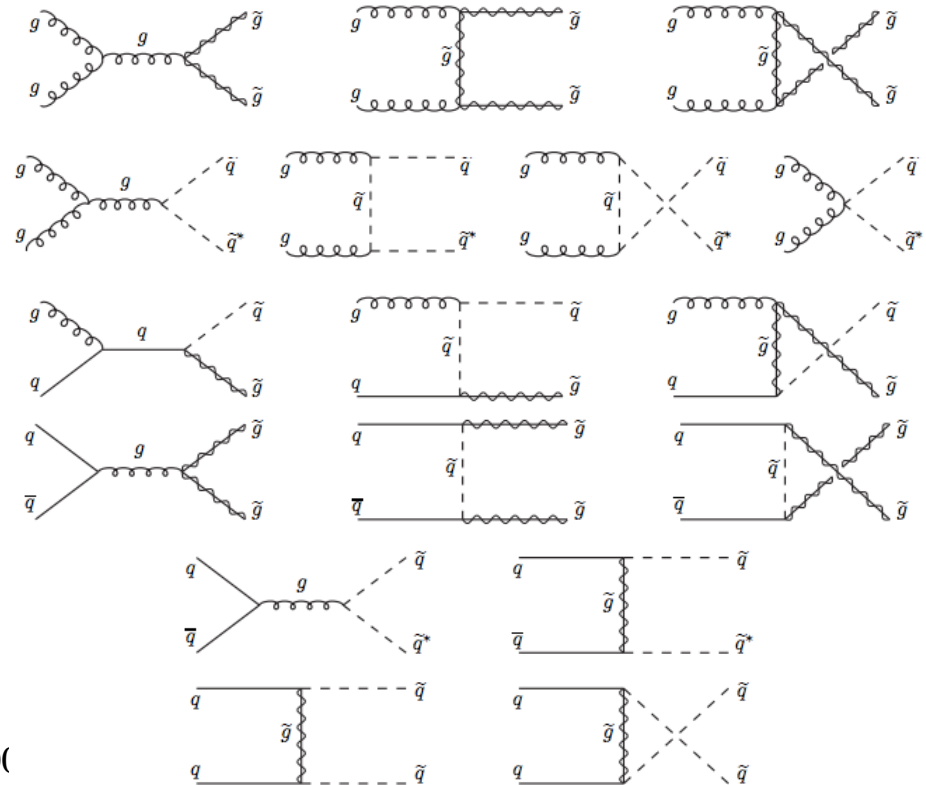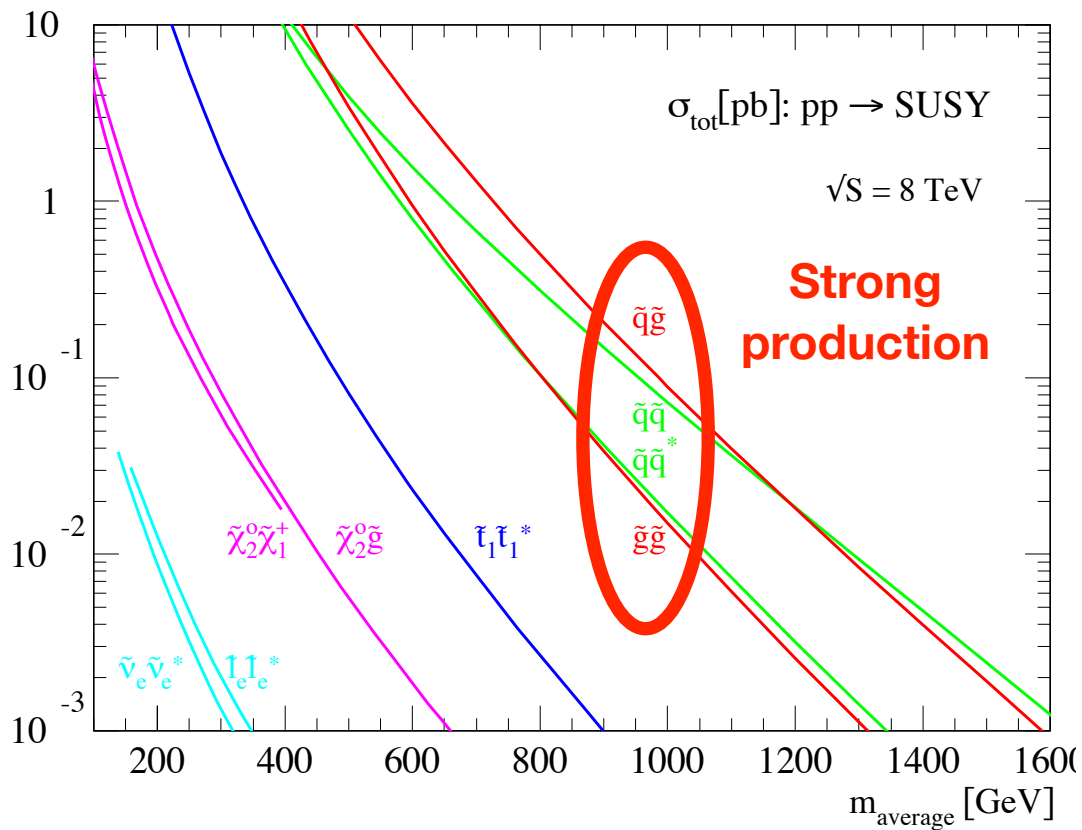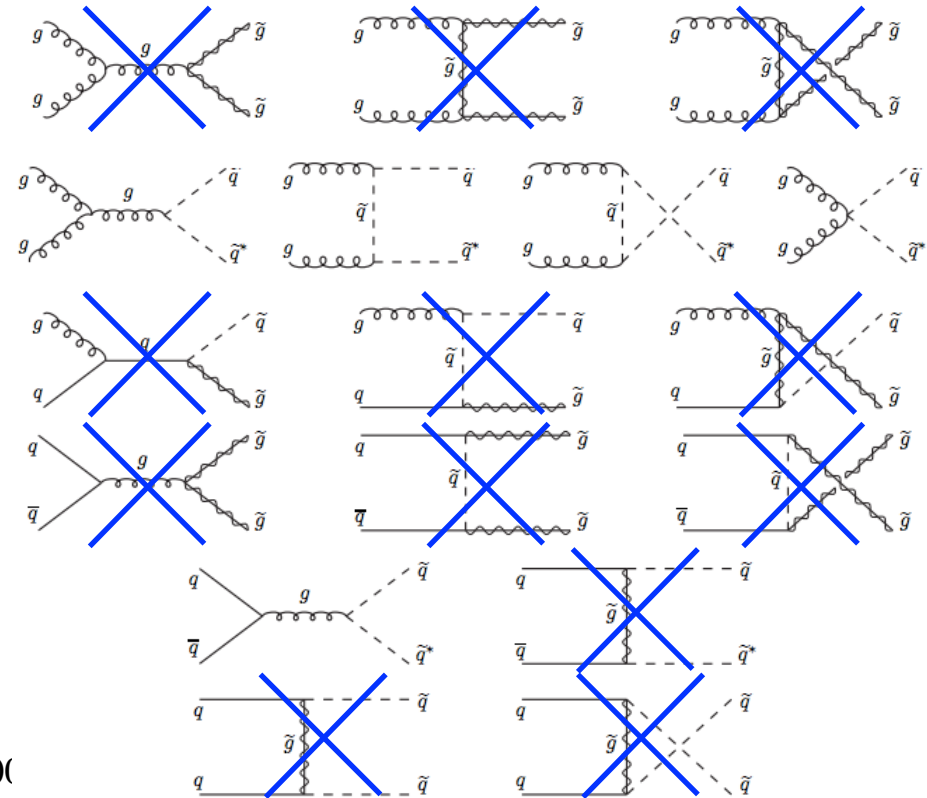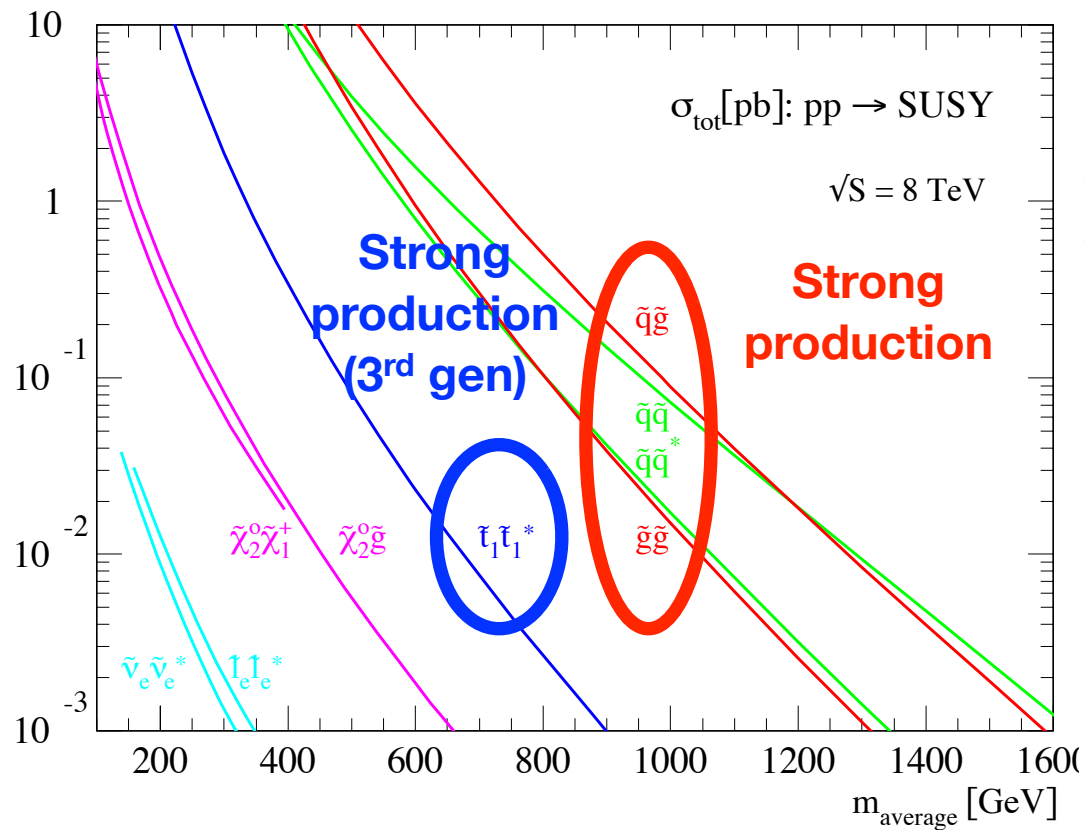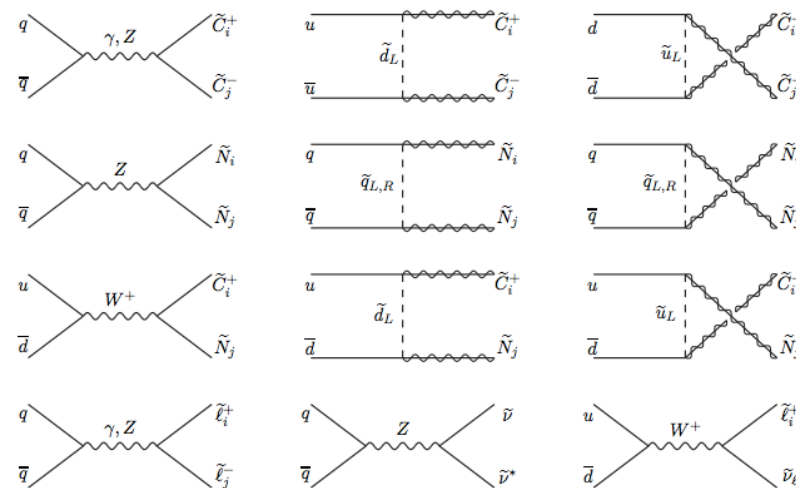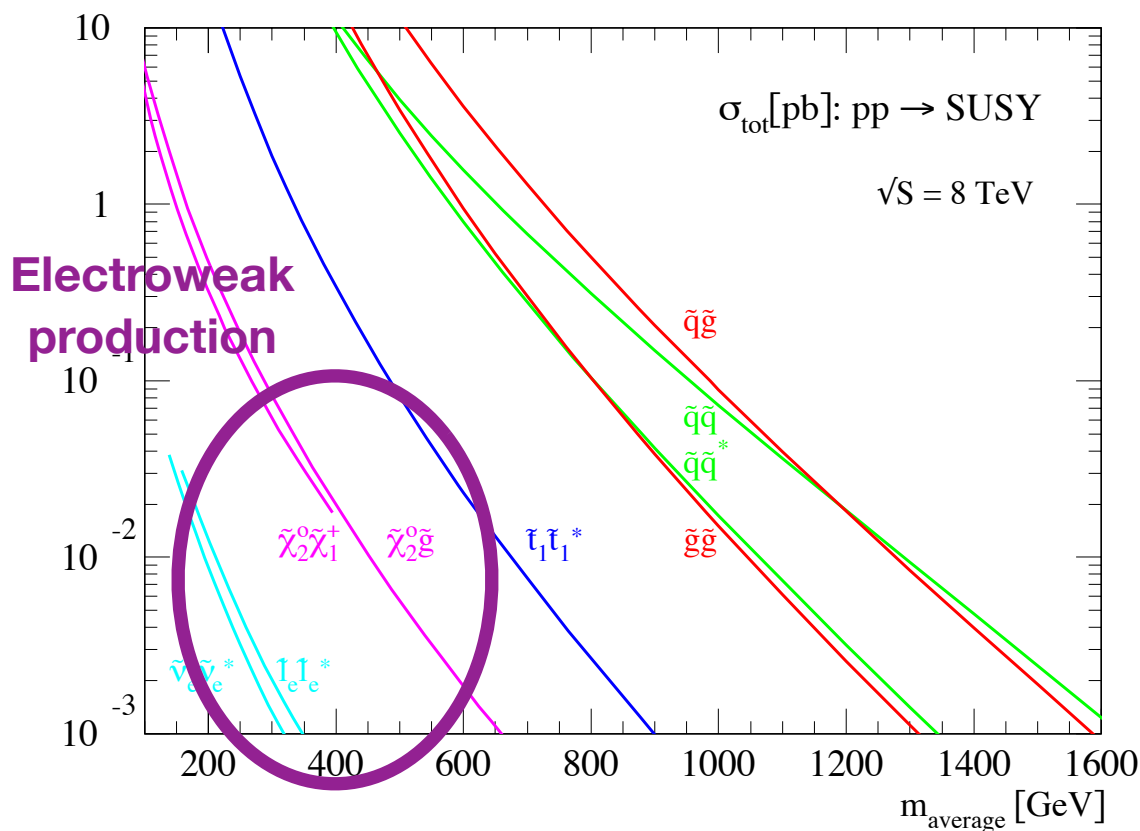
- **ATLAS has set up dedicated search strategies for all production mechanism**

- **Only strong production (mainly 3$^{rd}$ generation) covered in this seminar**

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# Standard Model background estimation

- Doing **SUSY searches** means primarily **understanding the Standard Model background**.

- **Few standard strategies** used all along the ATLAS SUSY analyses (centrally coordinated in the so-called background forum):

  - **Electroweak (and top) production:** rely on fixed order (or NLO) MC generators for predicting shapes of distributions:

    - Normalisation determined in dedicated control regions, shape prediction verified in the control regions and dedicated "validation" regions

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- **High cross section processes** can become a relevant through mechanisms difficult to model with MC:

- **multi-jet production** is a background for **0-lepton SUSY searches** (through, e.g., fake MET arising from a jet mismeasurement)

- **multi-jet (W+jets)** production is a background for **1-lepton (2-lepton)** analyses if a fake lepton is present in the event

- Dedicated data driven techniques used in such cases

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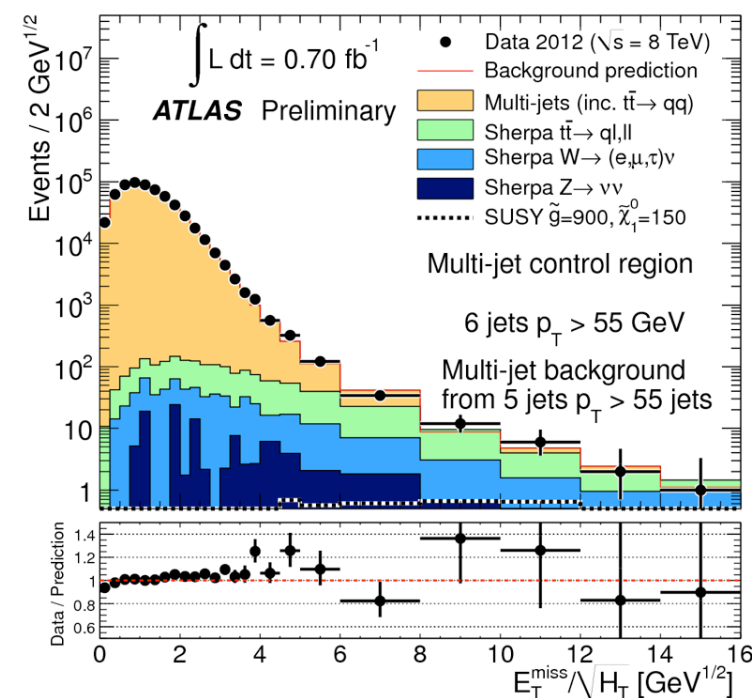
# Strong SUSY production

# Strong production

- Targeting generic strong production of gluinos and squarks.

- The exact decay chain depends on the SUSY mass hierarchy

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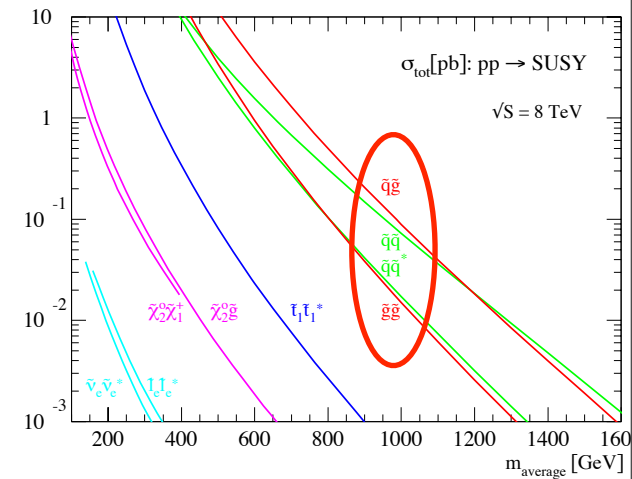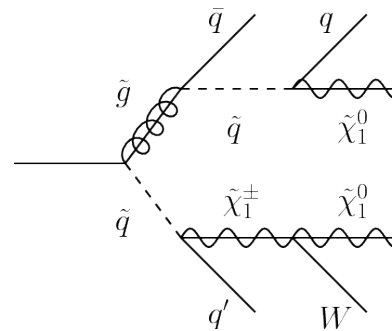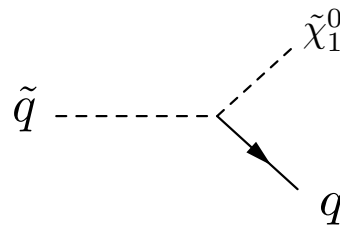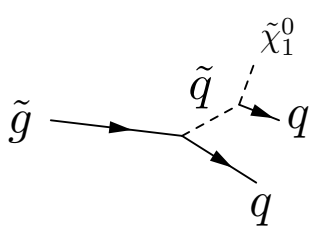
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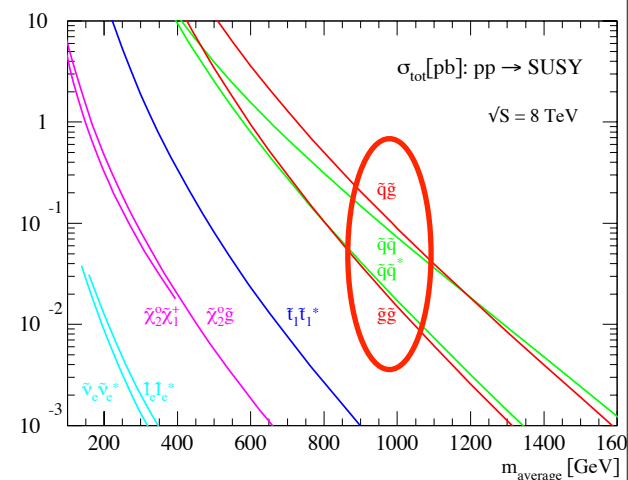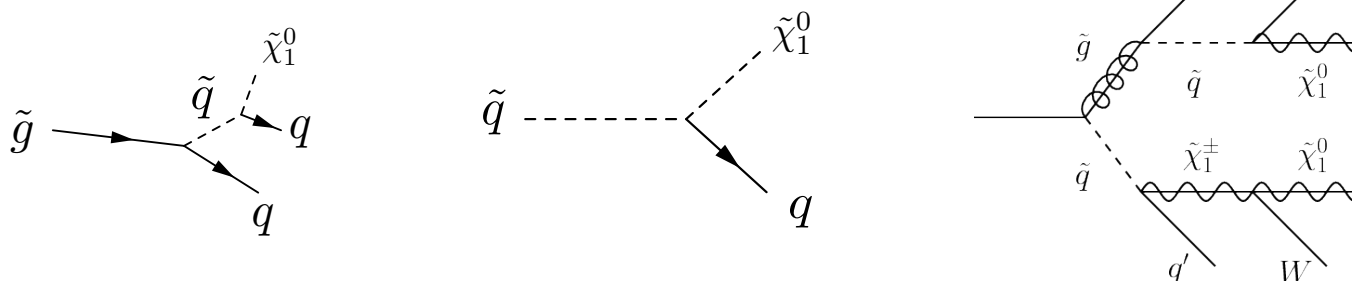


- Two analyses drive the limit with 8 TeV data

| | 0-lepton (ATLAS-CONF-2012-109) | 1-lepton (ATLAS-CONF-2012-104) |
|---|---|---|
| leptons | Veto any e or μ above 10 GeV | One isolated e or μ above 25 GeV |
| jets | 2 to 6 jets with $p_T$ > 60 GeV (leading jet $p_T$ > 130 GeV) | 4 jets with $p_T$ > 80 GeV |
| Other selections | MET > 160 GeV, reject multijet with cuts on MET/$M_{eff}$, and angle between jets and MET | MET > 250 GeV, $M_T$ > 100 GeV, additional selection on MET/$M_{eff}$ |
| Final selection | $M_{eff}$ | $M_{eff}$ |

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# Strong production

- **No excess** above SM in any of the signal regions:

  - interpreted **first as a model-independent 95% C.L. limit on** $\sigma_{vis}$ of BSM processes

  - then as **an exclusion limit in specific SUSY models**

$$\sigma_{vis} = \sigma \cdot A \cdot \varepsilon$$

| 1-lepton | Signal region | |
|---|---|---|
| | Electron | Muon |
| Observed events | 10 | 4 |
| Fitted background events | $9.0 \pm 2.8$ | $7.7 \pm 3.2$ |
| Fitted $t\bar{t}$ events | $6.0 \pm 2.2$ | $2.6 \pm 1.9$ |
| Fitted $W/Z$+jets events | $1.5 \pm 0.7$ | $4.2 \pm 2.3$ |
| Fitted other background events | $1.0 \pm 0.7$ | $0.9 \pm 0.3$ |
| Fitted multijet events | $0.4 \pm 0.6$ | $0.0 \pm 0.0$ |
| MC expected SM events | 9.5 | 11.5 |
| MC expected $t\bar{t}$ events | 5.7 | 4.6 |
| MC expected $W/Z$+jets events | 2.4 | 6.0 |
| MC expected other background events | 1.0 | 0.8 |
| Data-driven multijet events | 0.4 | 0.0 |

| | $\langle \epsilon\sigma \rangle^{95}_{obs}$ [fb] | $S^{95}_{obs}$ | $S^{95}_{exp}$ | $CL_B$ |
|---|---|---|---|---|
| Electron | 1.69 | 9.9 | $9.3^{+3.3}_{-2.6}$ | 0.59 |
| Muon | 1.09 | 6.4 | $8.3^{+3.4}_{-2.3}$ | 0.19 |

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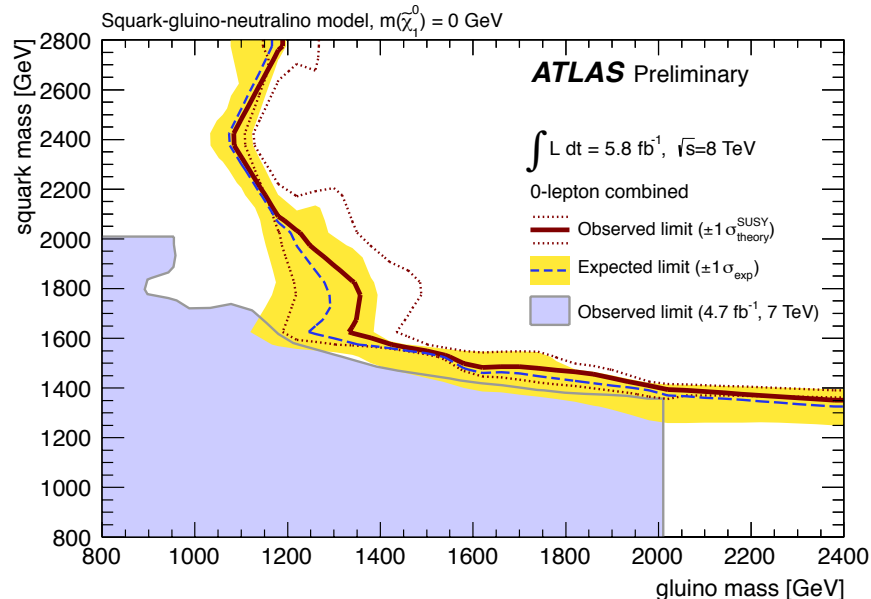
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1-lepton

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Squark-gluino-neutralino model, $m(\tilde{\chi}^0_1) = 0$ GeV

ATLAS Preliminary

$\int L\, dt = 5.8$ fb$^{-1}$, $\sqrt{s}=8$ TeV

0-lepton combined

— Observed limit ($\pm 1\,\sigma^{SUSY}_{theory}$)
-- Expected limit ($\pm 1\,\sigma_{exp}$)
Observed limit (4.7 fb$^{-1}$, 7 TeV)

- Simplified models: **assume degenerate 1st and 2nd generation squarks.** The only possible production processes are gg,gq,qq

- only possible processes (depending on masses)
$$\tilde{g} \rightarrow qq\tilde{\chi}^0_1,\ \tilde{g} \rightarrow \tilde{q}\tilde{\chi}^0_1,\ \tilde{q} \rightarrow q\tilde{\chi}^0_1$$
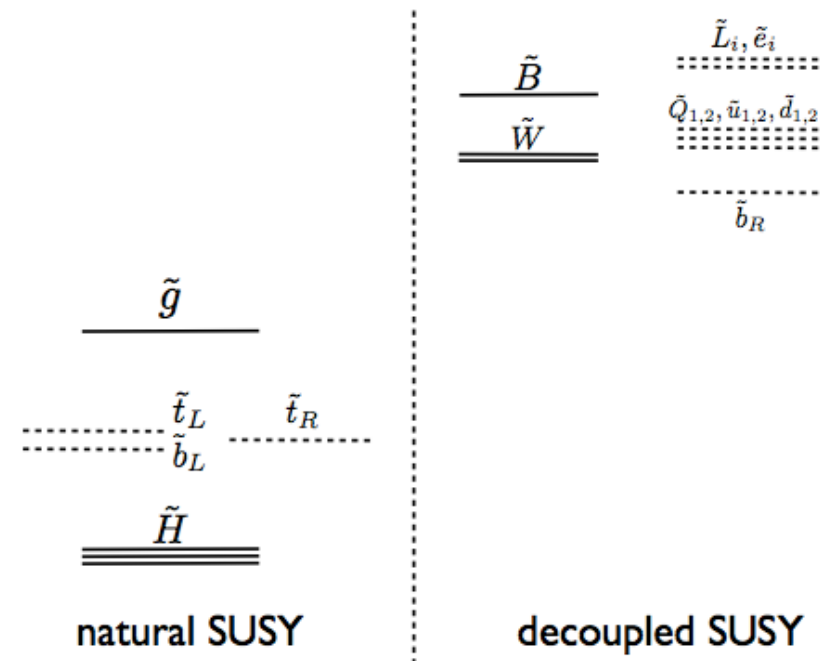
**Squark (gluino) masses below 1.3/1.4 (1.1) TeV excluded for any gluino (squark) mass**

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# Natural SUSY

- **She was not around the corner. Is she then gone?**

  - Or, more specifically: is the argument of SUSY solving the SM fine tuning not an argument anymore?

M.Papucci, J.Ruderman, A. Weiler

- "Naturalness" in SUSY driven by **the μ parameter, the stop mass** (the gluino mass to a lesser extent)

- "Light" stop(s), light sbottom (left), lighter higgsinos, not-so-heavy gluinos

- Almost no constraint on the other sparticles

- **The general MSSM can accommodate $m_h$ = 125/126 GeV and keep low fine tuning** (see, for example M. W. Cahill-Rowley et al., arXiv:1206.5800[hep-ph])

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# Gluino mediated stop production

- Gluinos and stops/sbottoms the only "light" strong interacting particles:

  - **gluino mediated stop/sbottom production**

  - **direct pair production of stops/sbottoms**
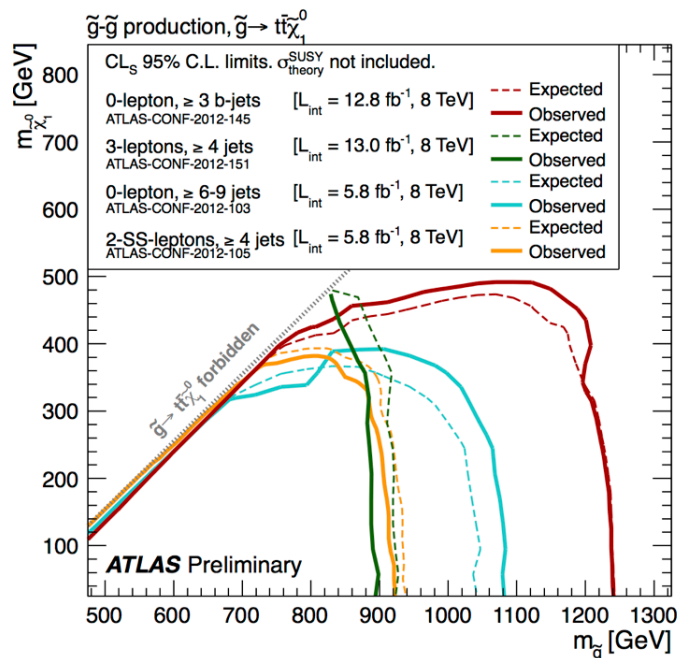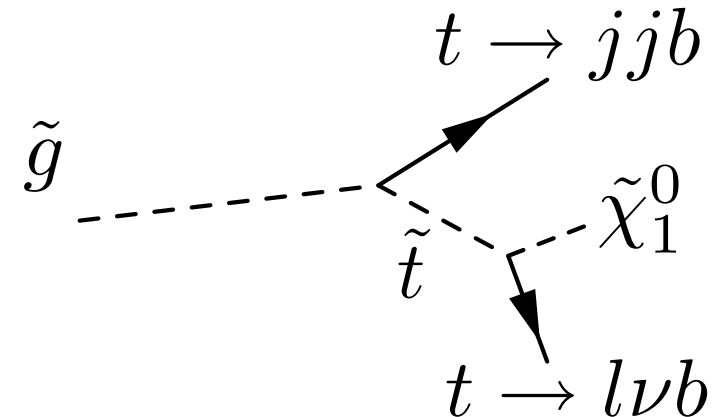
Friday, January 11, 2013

# Gluino mediated stop production

- Gluinos and stops/sbottoms the only "light" strong interacting particles:

  - **gluino mediated stop/sbottom production**

  - **direct pair production of stops/sbottoms**

$$t \rightarrow jjb$$

$$\tilde{g}$$

$$\tilde{t} \quad \tilde{\chi}_1^0$$

$$t \rightarrow l\nu b$$

- If gluino pair production dominant (and only stops not too heavy), then the decay is

$$\tilde{g} \rightarrow \tilde{t}t$$

- Final state that contains **MET (LSP), up to 4 b-jets, up to 12 jets, up to 4 leptons (possibly same sign)**

- Three different analyses target this final state:

  - **3-b jets plus MET** (up to 6 jets) - ATLAS-CONF-2012-145

  - **2 SS leptons + MET + 4 jets** - ATLAS-CONF-2012-105

  - **multijet (up to 9 jets)** - ATLAS-CONF-2012-103

  - **3-leptons + MET** - ATLAS-CONF-2012-151

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# direct 3ʳᵈ generation squark production

- The **stops (and the sbottom left)** constrained by naturalness to be **not heavier than ~ 1 TeV**

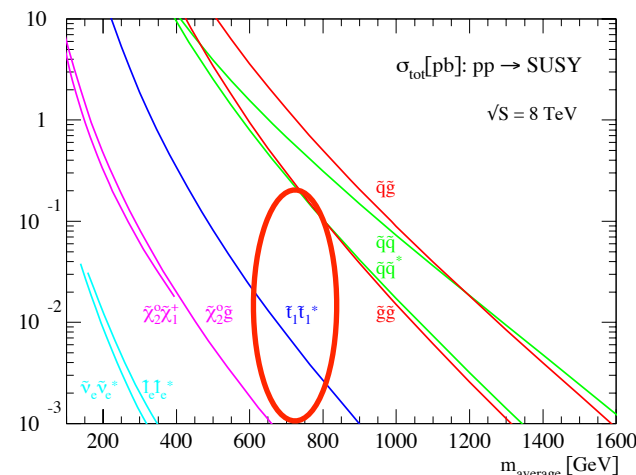- Wide, dedicated effort for **direct stop production search** in ATLAS

- The $t_1$ decay branching ratios depend strongly on:
  - Mass hierarchy ($\tilde{t}_1$, $\tilde{X}_1^0$, $\tilde{X}_1^\pm$)
  - Chirality of the stop and of the $\tilde{X}_1^0$, $\tilde{X}_1^\pm$

- Several analyses used:
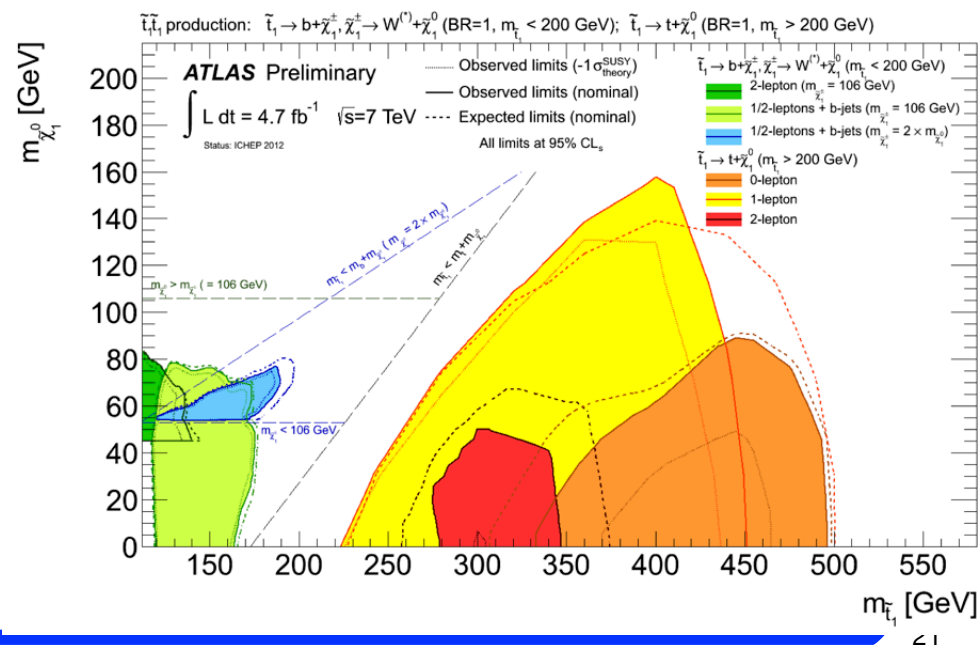  - $\tilde{t}_1 \rightarrow t\tilde{X}_1^0$: 0-lepton, 1-lepton*, 2-leptons
  - $\tilde{t}_1 \rightarrow b\tilde{X}_1^\pm$: 1-lepton, 2-leptons*, 0-lepton (2b + MET)*

  - * = analyses updated for $\sqrt{s}$ = 8 TeV or new

## 2011 status

# 2 b-jets + MET

- Generic topology of many interesting physics channels:

  - In particular sbottom and stop pair production

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# 2 b-jets + MET

- Generic topology of many interesting physics channels:

  - In particular sbottom and stop pair production

- If the chargino and neutralino are degenerate in mass, the final states are identical ⇒ **target small Δm($\widetilde{X}_1^\pm$,$\widetilde{X}_1^0$)**
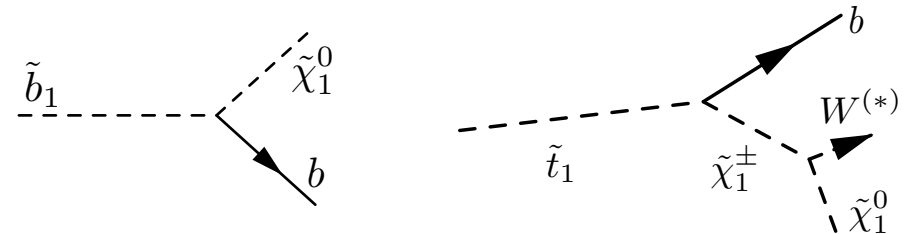
- Basically two signal regions used

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# 2 b-jets + MET
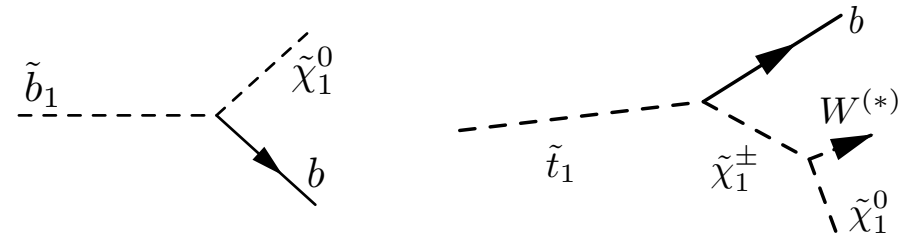
- Generic topology of many interesting physics channels:
  - In particular sbottom and stop pair production



- If the chargino and neutralino are degenerate in mass, the final states are identical $\Rightarrow$ **target small $\Delta m(\widetilde{X}_1^{\pm},\widetilde{X}_1^{0})$**

- Basically two signal regions used

- $m_{CT}$: boost-corrected contransverse mass
  - $m_{CT}^2(b_1,b_2) = (E_T(b_1) + E_T(b_2))^2 - (\mathbf{p}_T(b_1) - \mathbf{p}_T(b_2))^2$
  - for pair produced particles decaying into visible and invisible particles
  - It has an end-point at $(m_{prod}^2 - m_{inv}^2)/m_{prod}^2$

- **SR1(for large $\Delta m(\widetilde{b}/\widetilde{t}, \widetilde{X}_1^{0})$):**
  - Look for 2 b-jets (veto on third jet), large MET
  - Use $M_{CT}$ to suppress top (end-point at 135 GeV)
  - Main background (at high $M_{CT}$): Z ($\rightarrow \nu\nu$)+b-jets
  - SR2 is similar

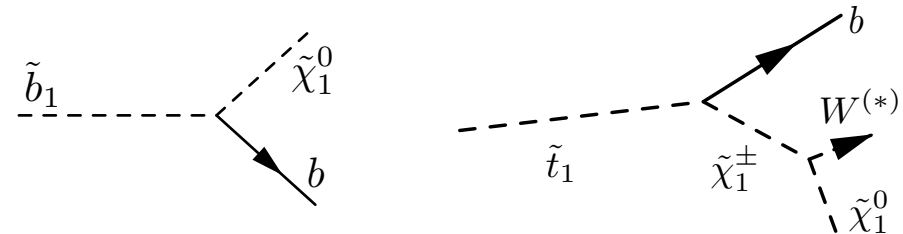Friday, January 11, 2013

# 2 b-jets + MET

- Generic topology of many interesting physics channels:
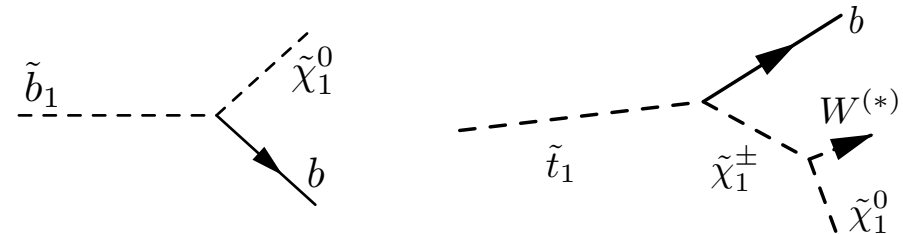
  - In particular sbottom and stop pair production



- If the chargino and neutralino are degenerate in mass, the final states are identical ⇒ **target small $\Delta m(\widetilde{X}_1^\pm, \widetilde{X}_1^0)$**

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- $m_{CT}$: boost-corrected contransverse mass

  - $m_{CT}^2(b_1, b_2) = (E_T(b_1) + E_T(b_2))^2 - (\mathbf{p}_T(b_1) - \mathbf{p}_T(b_2))^2$

  - for pair produced particles decaying into visible and invisible particles

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  - Main background (at high $M_{CT}$): Z ($\rightarrow \nu\nu$)+b-jets

  - SR2 is similar

- **SR3 (for small $\Delta m(\widetilde{b}/\widetilde{t}, \widetilde{X}_1^0)$):**

  - Focus on events with a hard ISR jet produced

  - Hard, non b-tagged leading jet, two additional b-jets

  - Veto on additional hadronic activity

  - Main background: top pair production

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# Control region definition

- Background estimation

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# Control region definition

- **Background estimation**

- top/W control region:

  - 2 b-jets

  - 1-lepton, 40 GeV < $M_T$ < 100 GeV, similar selection as SR

  - At high $M_{CT}$ W and top both relevant

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# Control region definition

• **Background estimation**

<table>
<tr><td valign="top">

• top/W control region:

  • 2 b-jets

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  • At high $M_{CT}$ W and top both relevant

</td><td valign="top">

• Z control region:

  • 2 b-jets

  • 2-lepton same flavour, select the Z peak

  • "Mimic" MET by "neutrinising" the leptons

</td></tr>
</table>

Friday, January 11, 2013
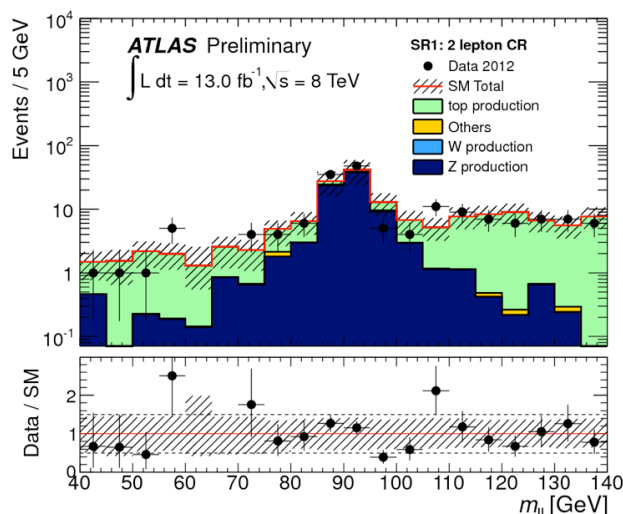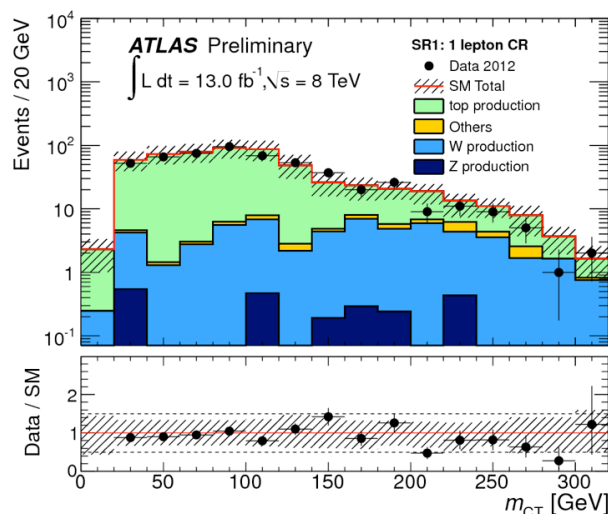
# Control region definition

- **Background estimation**

<table>
<tr>
<td valign="top">

- top/W control region:
  - 2 b-jets
  - 1-lepton, 40 GeV < $M_T$ < 100 GeV, similar selection as SR
  - At high $M_{CT}$ W and top both relevant

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- Z control region:
  - 2 b-jets
  - 2-lepton same flavour, select the Z peak
  - "Mimic" MET by "neutrinising" the leptons

</td>
<td valign="top">

- top control region:
  - 2 b-jets
  - 2-lepton different flavour
  - Very pure top control region

</td>
</tr>
</table>

Friday, January 11, 2013
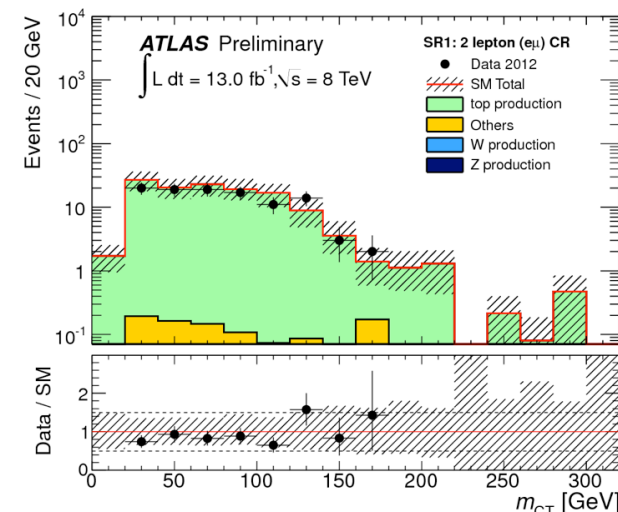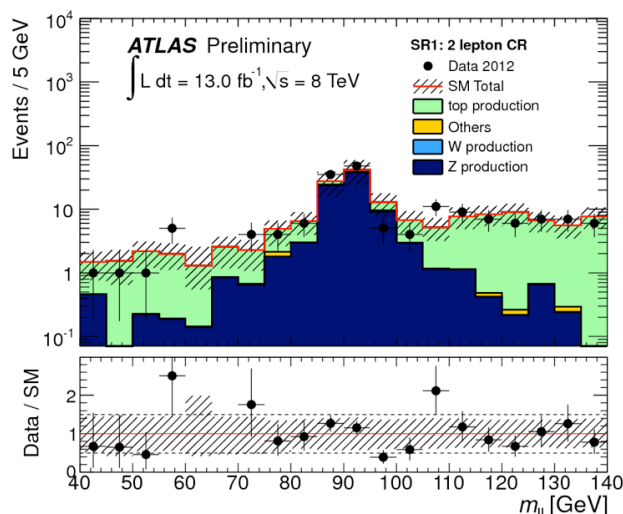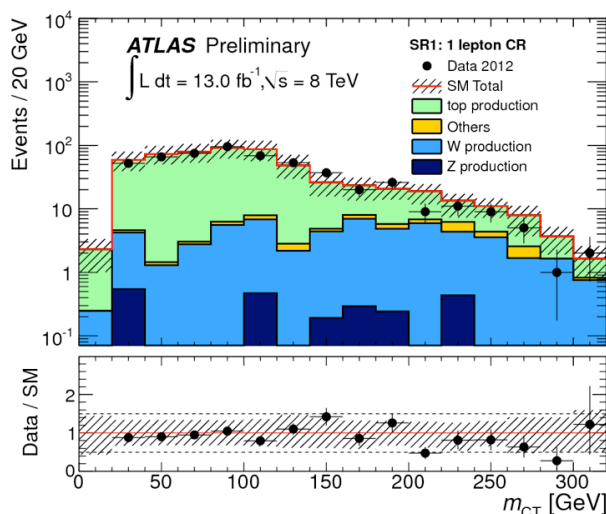
# Control region counts and systematics

| Channel | $CR1L\_SR1$ | $CR2L\_SR1$ | $CR2LDF\_SR1$ |
|---|---|---|---|
| Observed events | 104 | 102 | 51 |
| Fitted bkg events | $104 \pm 11$ | $102 \pm 11$ | $51 \pm 7$ |
| Top production | $70 \pm 16$ | $18 \pm 4$ | $50 \pm 7$ |
| Z production | $1.5 \pm 0.4$ | $82 \pm 12$ | — |
| W production | $25 \pm 19$ | — | — |
| Others | $8 \pm 4.$ | $2.4 \pm 1.3$ | $0.8 \pm 0.4$ |

- Normalisation factors for the backgrounds in control regions close to 1 for top, to 1.2 for Z

- Systematic uncertainties:

  - b-tagging uncertainties (~15%)

  - jet energy scale uncertainty (~10%)

  - Z production theoretical uncertainties (5%)



- Results **compatible with SM background predictions** in all signal regions
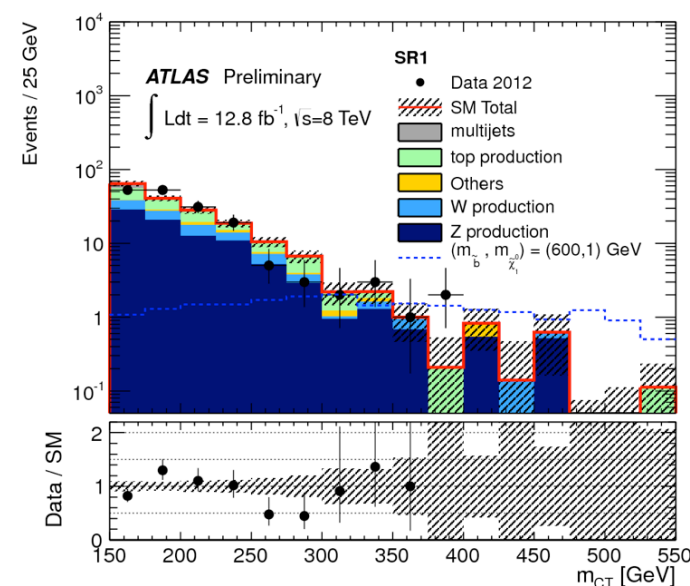
| Channel | SR1, $m_{CT}$ selection | | | | SR2 | SR3 | |
|---|---|---|---|---|---|---|---|
| | 150 GeV | 200 GeV | 250 GeV | 300 GeV | | SR3a | SR3b |
| Observed | 172 | 66 | 16 | 8 | 104 | 207 | 21 |
| SM Total | $176 \pm 25$ | $71 \pm 11$ | $25 \pm 4$ | $7.4 \pm 1.7$ | $95 \pm 11$ | $203 \pm 35$ | $27 \pm 5$ |
| Top production | $45 \pm 13$ | $17 \pm 6$ | $7 \pm 3$ | $1.6 \pm 0.6$ | $15 \pm 4$ | $146 \pm 40$ | $15 \pm 5$ |
| Z production | $85 \pm 15$ | $36 \pm 6$ | $12 \pm 2$ | $4.0 \pm 0.9$ | $60 \pm 9$ | $27 \pm 9$ | $7 \pm 2$ |
| W production | $28 \pm 23$ | $12 \pm 10$ | $4 \pm 3$ | $1 \pm 1$ | $15 \pm 5$ | $22 \pm 7$ | $4 \pm 1$ |
| Others | $6 \pm 3$ | $4 \pm 2$ | $1.4 \pm 0.8$ | $0.7 \pm 0.4$ | $4 \pm 2$ | $4 \pm 2$ | $1.5 \pm 0.9$ |
| Multijet production | $12 \pm 12$ | $2 \pm 2$ | $0.2 \pm 0.2$ | $0.01 \pm 0.01$ | $0.6 \pm 0.6$ | $4 \pm 4$ | — |

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# 0-lepton, 2-b jets stop searches

- 95% C.L. model independent upper limits on BSM event yield and $\sigma_{vis}$

| Signal region | Bkg. estimate | Obs. data | 95% CL UL on BSM event yield | | 95% CL UL on $\sigma_{vis}$ (fb) | |
|---|---|---|---|---|---|---|
| | | | expected | observed | expected | observed |
| SR1 ($m_{CT} > 150$ GeV) | $176 \pm 25$ | 172 | 55 | 54 | 4.2 | 4.1 |
| SR1 ($m_{CT} > 200$ GeV) | $71 \pm 11$ | 66 | 25 | 22 | 1.9 | 1.7 |
| SR1 ($m_{CT} > 250$ GeV) | $25 \pm 4$ | 16 | 12.5 | 7.9 | 0.96 | 0.61 |
| SR1 ($m_{CT} > 300$ GeV) | $7.4 \pm 1.7$ | 8 | 7.5 | 8.0 | 0.58 | 0.62 |
| SR2 | $95 \pm 11$ | 104 | 32 | 39 | 2.5 | 3.0 |
| SR3a | $203 \pm 35$ | 207 | 54 | 54 | 4.2 | 4.2 |
| SR3b | $27 \pm 5$ | 21 | 13.1 | 9.6 | 1.0 | 0.74 |

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# 0-lepton, 2-b jets stop searches

| Signal region | Bkg. estimate | Obs. data | 95% CL UL on BSM event yield | | 95% CL UL on $\sigma_{vis}$ (fb) | |
|---|---|---|---|---|---|---|
| | | | expected | observed | expected | observed |
| SR1 ($m_{CT} > 150$ GeV) | $176 \pm 25$ | 172 | 55 | 54 | 4.2 | 4.1 |
| SR1 ($m_{CT} > 200$ GeV) | $71 \pm 11$ | 66 | 25 | 22 | 1.9 | 1.7 |
| SR1 ($m_{CT} > 250$ GeV) | $25 \pm 4$ | 16 | 12.5 | 7.9 | 0.96 | 0.61 |
| SR1 ($m_{CT} > 300$ GeV) | $7.4 \pm 1.7$ | 8 | 7.5 | 8.0 | 0.58 | 0.62 |
| SR2 | $95 \pm 11$ | 104 | 32 | 39 | 2.5 | 3.0 |
| SR3a | $203 \pm 35$ | 207 | 54 | 54 | 4.2 | 4.2 |
| SR3b | $27 \pm 5$ | 21 | 13.1 | 9.6 | 1.0 | 0.74 |

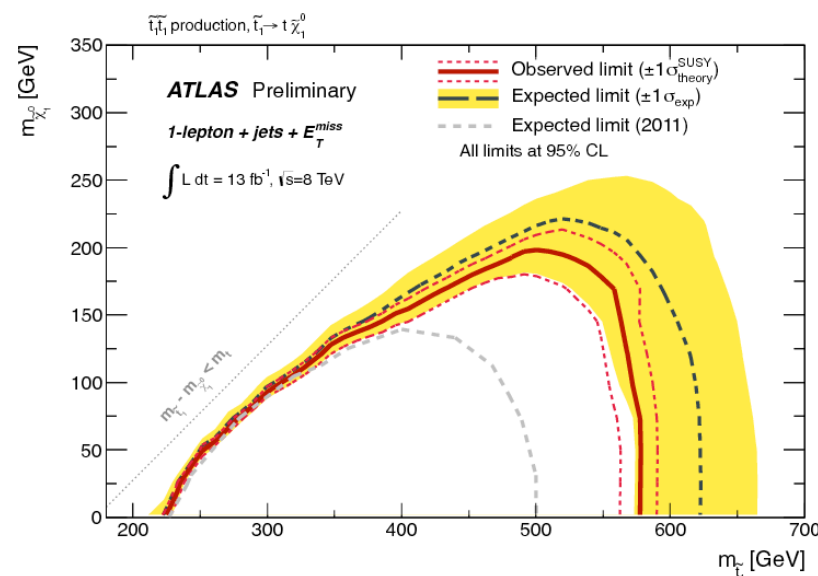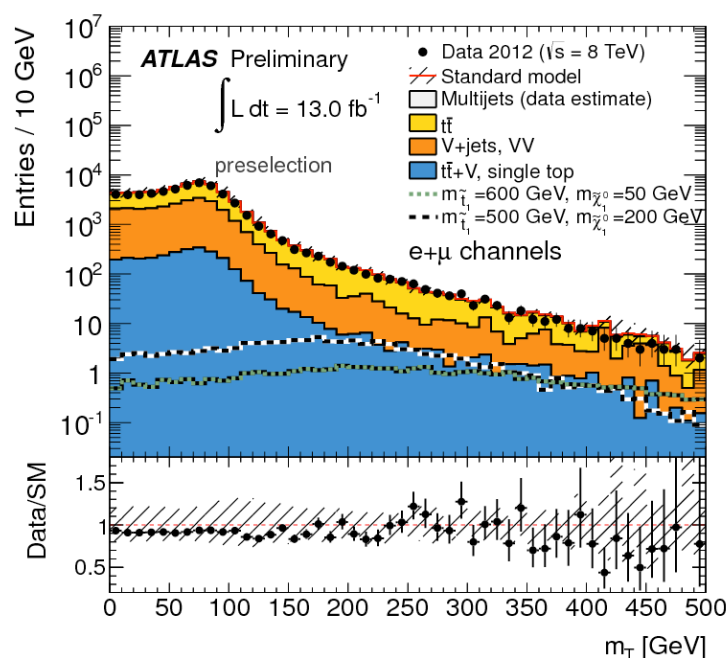- 95% C.L. model independent upper limits on BSM event yield and $\sigma_{vis}$

- 95% C.L. limit **very similar for the sbottom and the stop case if $\Delta m(\tilde{X}_1^{\pm}, \tilde{X}_1^0)$ = 5 GeV**

- A clear **loss of acceptance** (because of lepton and jet veto) if **$\Delta m(\tilde{X}_1^{\pm}, \tilde{X}_1^0)$ = 20 GeV**

- **$\tilde{t} \rightarrow b\tilde{X}_1^{\pm}$ (BR 100%) excluded up to $m_{\tilde{t}} \sim 600$ GeV for nearly degenerate chargino and neutralino masses**
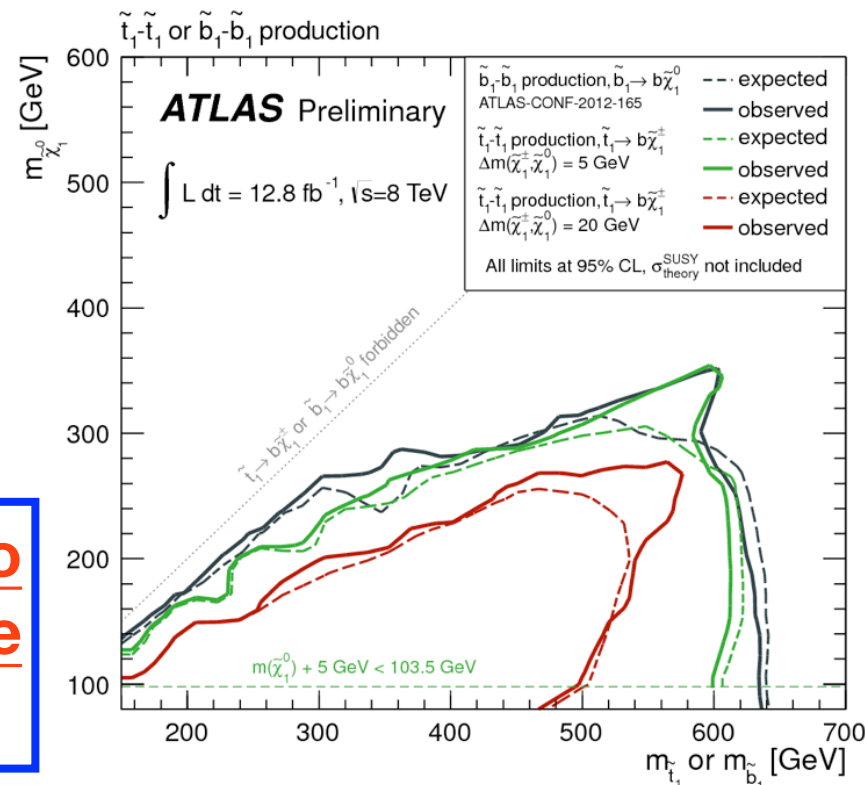


$\tilde{t}_1\text{-}\tilde{t}_1$ or $\tilde{b}_1\text{-}\tilde{b}_1$ production

**ATLAS** Preliminary

$\int L\, dt = 12.8$ fb$^{-1}$, $\sqrt{s}$ = 8 TeV

$\tilde{b}_1\text{-}\tilde{b}_1$ production, $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$ — expected / observed
ATLAS-CONF-2012-165

$\tilde{t}_1\text{-}\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$
$\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$ = 5 GeV — expected / observed

$\tilde{t}_1\text{-}\tilde{t}_1$ production, $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^{\pm}$
$\Delta m(\tilde{\chi}_1^{\pm}, \tilde{\chi}_1^0)$ = 20 GeV — expected / observed

All limits at 95% CL, $\sigma_{theory}^{SUSY}$ not included

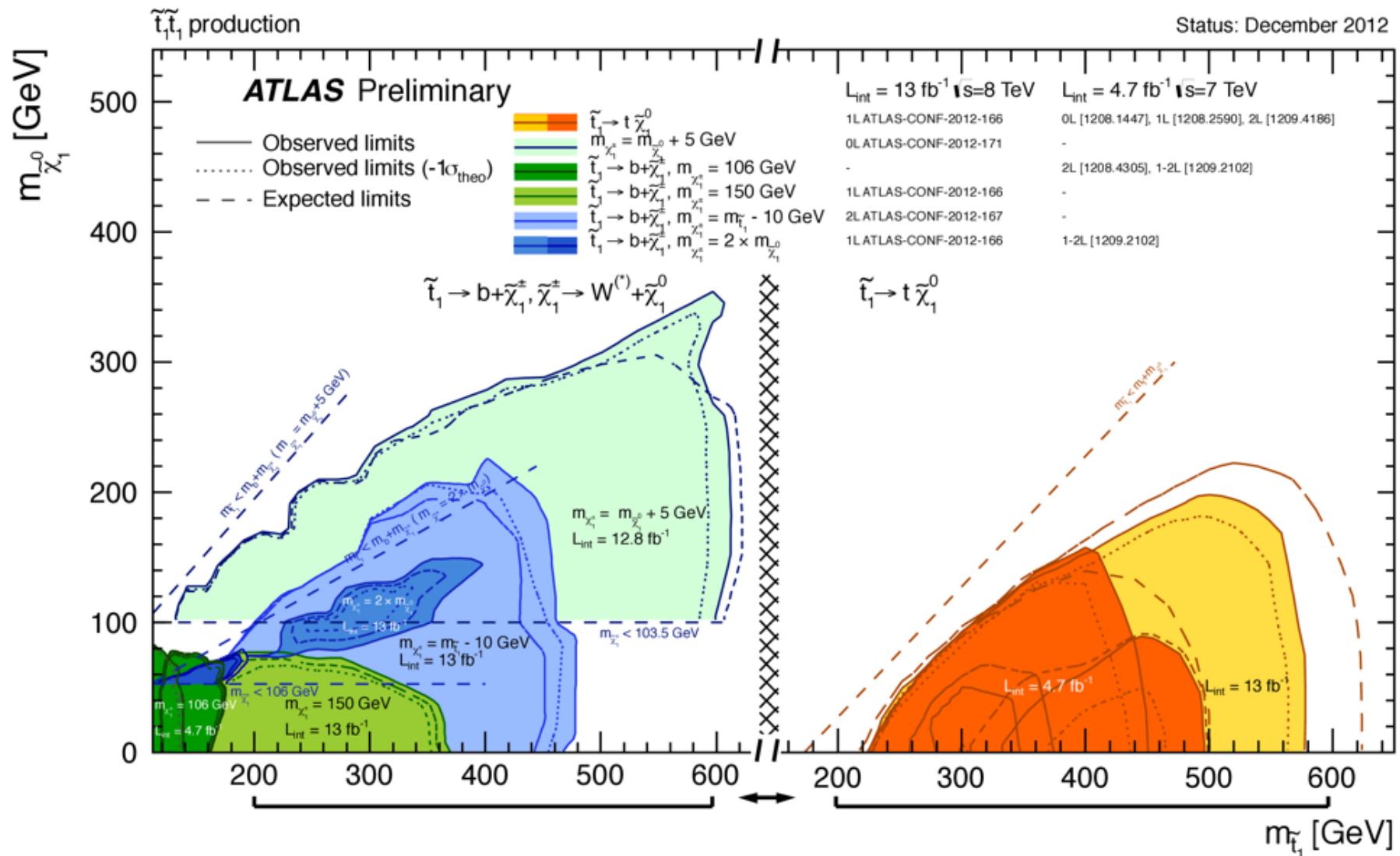$m(\tilde{\chi}_1^0)$ + 5 GeV < 103.5 GeV

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# 1-lepton stop searches (ATLAS-CONF-2012-166)

- Dedicated **1-lepton analysis** dominates the reach for $t_1$ pair production $(\tilde{t}_1 \to \tilde{t} X_1^0)$

- Basic strategy: **select top-like events with large $M_T$ and MET**.

- Main background: **tt → llbb + MET (dominant at large $M_T$)**

- Dedicated effort to **improve the second lepton veto** (isolated tracks - tau-like events)

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# Direct stop search summary

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# What is missing? (3$^{rd}$ gen)

- My own to-do list for the next **few months/years**:

  - Improve limits at **high stop mass**:

    - boosted top reconstruction?

- **Mixed decays (50% $\tilde{t}_1 \rightarrow t\tilde{X}_1^0$, 50% $\tilde{t}_1 \rightarrow b\tilde{X}_1^\pm$)** still not considered (and somewhat favoured, actually)

- Complete the investigation in **the low mass region** (exclude independently of the stop parameters and mass hierarchy).



Light Stop Decays

SUSY and the LHC - 8th January 2013 - LBNL

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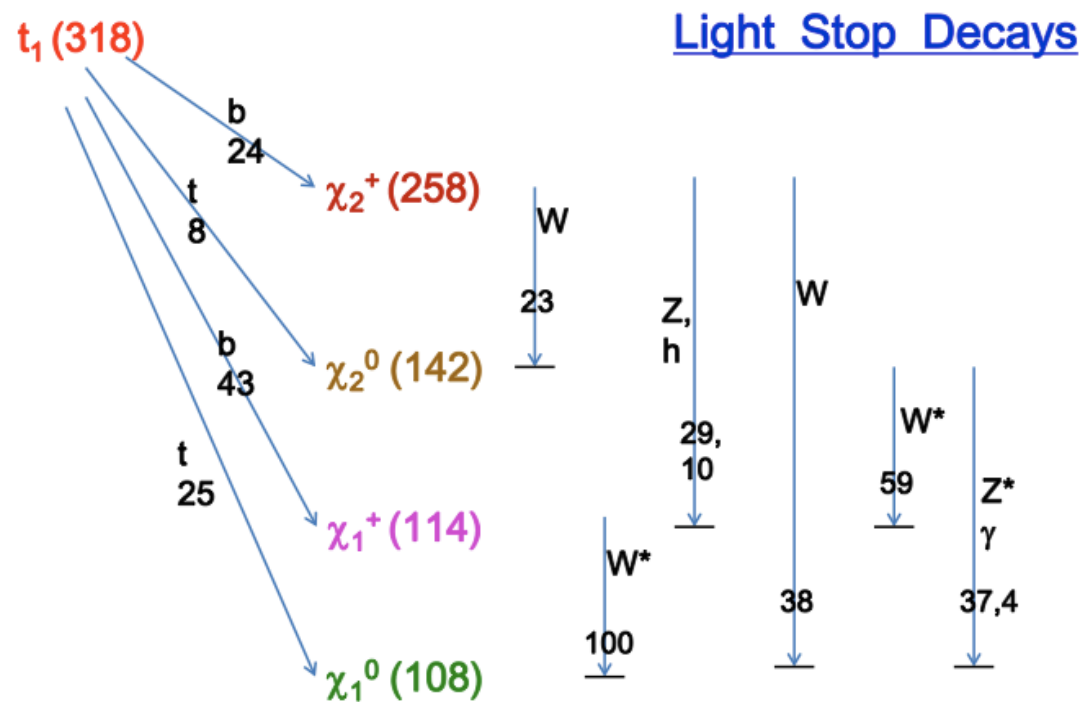
# Prospects for SUSY searches at 13/14 TeV

- LHC is **foreseen to run at 13/14 TeV** after 2015 and **integrate about 300 fb$^{-1}$**.

- Increased **energy and pileup conditions** (highly dependent on the bunch spacing)

  - Impact mainly on trigger conditions:

    - Short term: improve on trigger strategy - trigger on topologies

    - Long term: dedicated hardware/software upgrades: improved calorimeter readout at early trigger stages, single track trigger, etc.

- Expect to deal with **increased p$_T$ thresholds** at the beginning, especially for leptons (lowest unprescaled lepton trigger of p$_T$ > 33 GeV w.r.t. current 25 GeV

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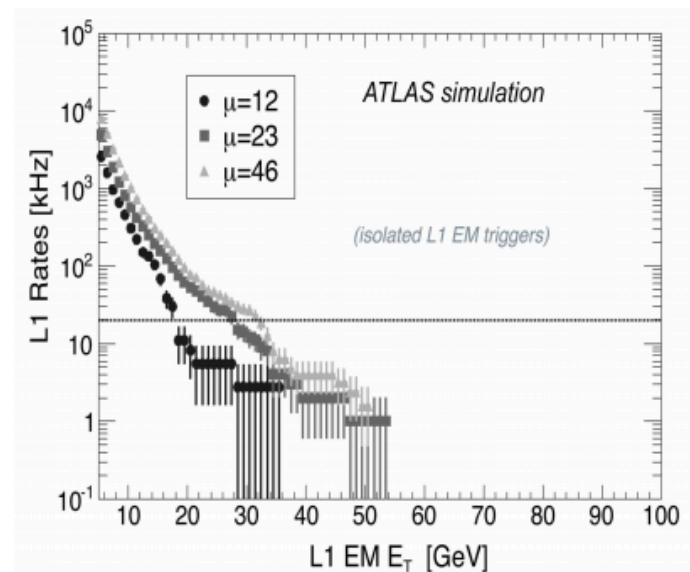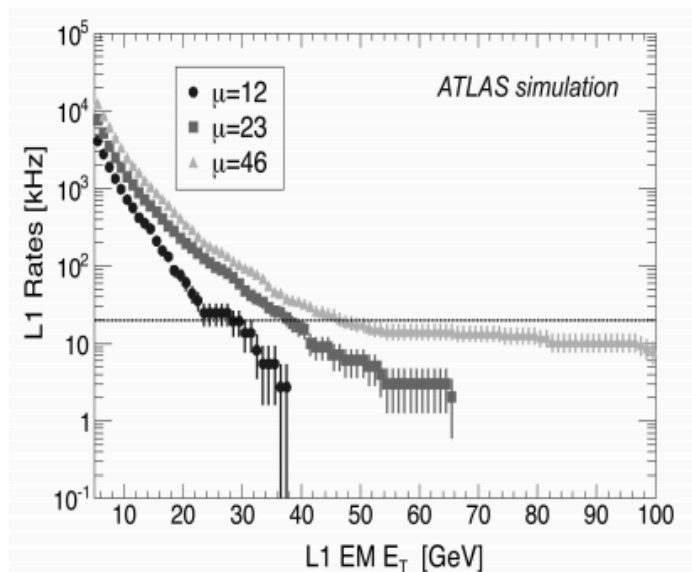
# Prospects with 13/14 TeV

- Project the sensitivity of the analyses to **13/14 TeV**

- **...**assuming **realistic running conditions** and no improvement on the analyses (!)

- A lot still to be said about EW scale SUSY

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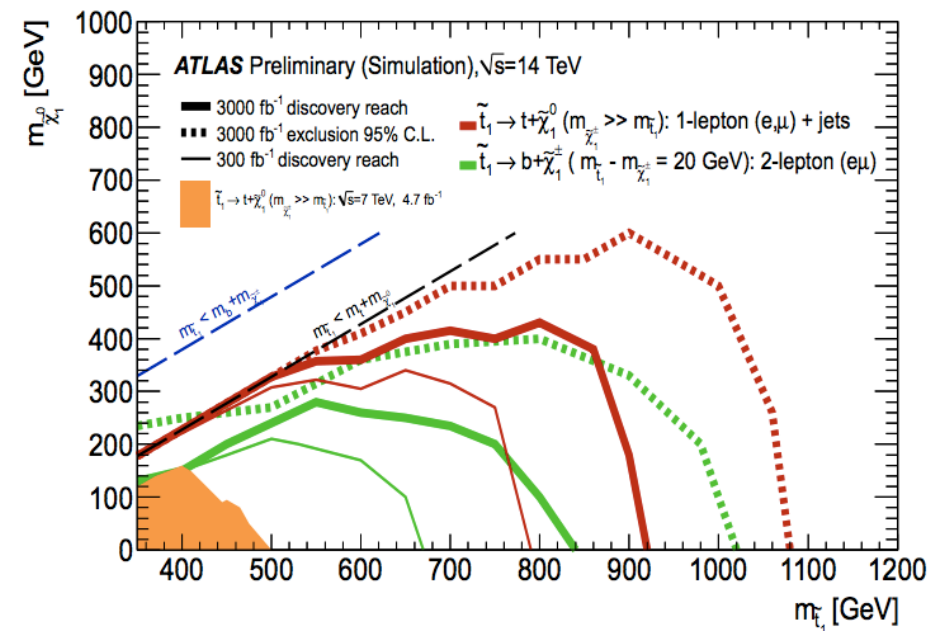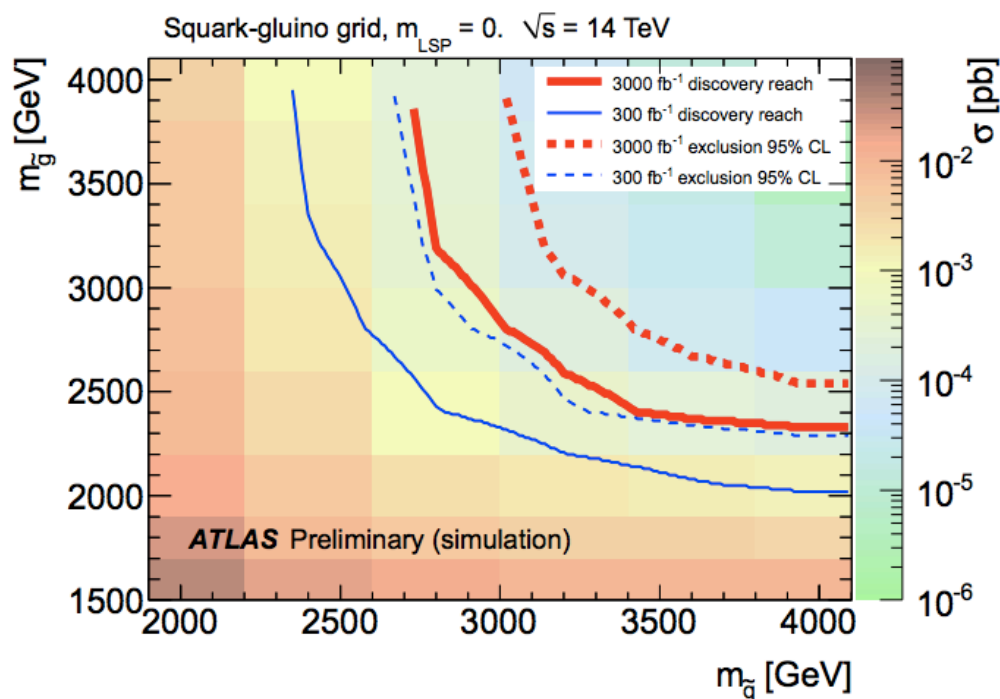
# Summary

- SUSY **was not around the corner.** Degenerate $1^{st}$ **and** $2^{nd}$ **generation squarks (gluinos)** are excluded up to **m = 1.5 TeV (1.2 TeV)** for $m_{LSP} = 0$.

- Searches for direct production **of third generation squarks** are also very well advanced.

  - **Stops decaying (only) into top-LSP excluded up to ~560 GeV** for massless LSP. Large fraction of the available parameter space also excluded for $\tilde{t} \rightarrow b\tilde{X}_1^{\pm}$

  - The 14 TeV data will allow to probe up to $m_{stop} \sim 1$ TeV

- The **startup of the LHC** has been a fruitful and exciting period for SUSY searches

  - Waiting for the 13/14 TeV running

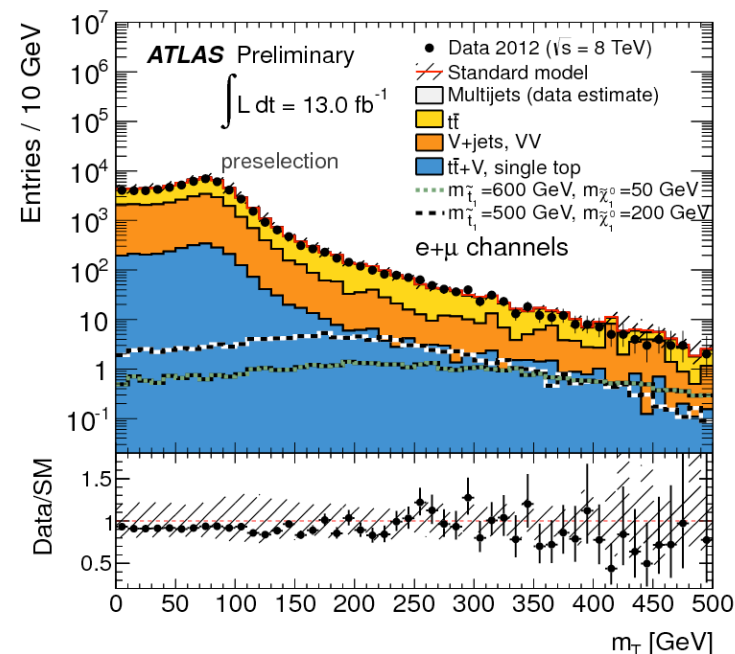Friday, January 11, 2013

# BACKUP

# 1-lepton stop searches (ATLAS-CONF-2012-166)

- Dedicated **1-lepton analysis** dominates the reach for $t_1$ pair production ($t_1 \to tX_1^0$)

- Basic strategy: **select top-like events with large $M_T$ and MET**.

- Main background: **tt→llbb + MET (dominant at large $M_T$)**

- Dedicated effort to **improve the second lepton veto** (isolated tracks - tau-like events)

Select $m_{jjj}$ compatible with had top decay

| Requirement | SRD | SRE | SRtN1 | SRtN2 | SRtN3 | SRbC |
|---|---|---|---|---|---|---|
| $\Delta\phi(j_1, \vec{p}_T^{\,miss}) >$ | 0.8 | 0.8 | 0.8 | - | 0.8 | 0.8 |
| $\Delta\phi(j_2, \vec{p}_T^{\,miss}) >$ | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 | 0.8 |
| $E_T^{miss}$ [GeV] $>$ | 225 | 275 | 150 | 200 | 225 | 150 |
| $E_T^{miss}/\sqrt{H_T}$ [GeV$^{1/2}$] $>$ | 11 | 11 | 8 | 13 | 11 | 7 |
| $m_T$ [GeV] $>$ | 130 | 140 | 140 | 140 | 180 | 120 |
| $m_T$ [GeV] $<$ | - | - | 250 | - | - | - |
| $am_{T2}$ [GeV] $>$ | - | - | - | 170 | 200 | - |
| $m_{T2}^\tau$ [GeV] $>$ | - | - | - | - | 120 | - |
| $N^{iso-trk} = 0$ | - | - | - | - | - | Yes |
| $A \times \varepsilon$ benchmark point | - | - | 0.06% | 0.9% | 2.8% | 0.7% |

SUSY and the LHC - 8th January 2013 - LBNL

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# 1-lepton stop searches

- **top pair production background** normalised in control region (60 GeV < $M_T$ < 90 GeV). **Same for W** (anti-b-tag)

- Fake lepton background obtained with Matrix Method

- No excess in any of the signal regions.

- Result interpreted in $t_1 t_1$ production with $t_1 \rightarrow tX_1^0$ (BR 100%) or $t_1 \rightarrow bX_1^{\pm}$ (BR 100%)

Friday, January 11, 2013
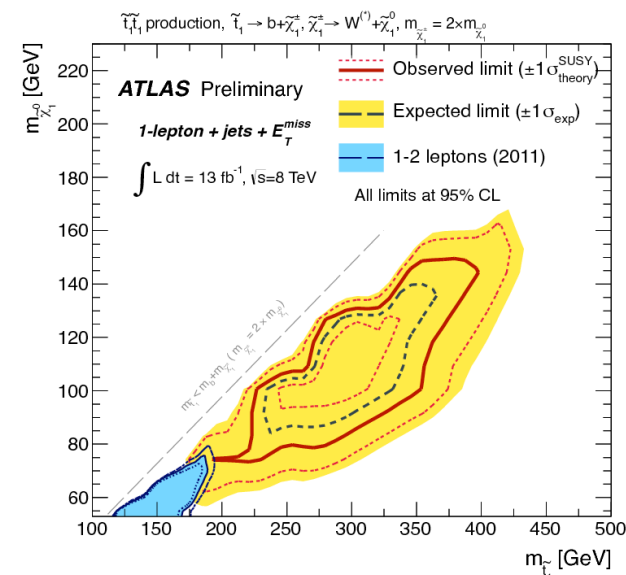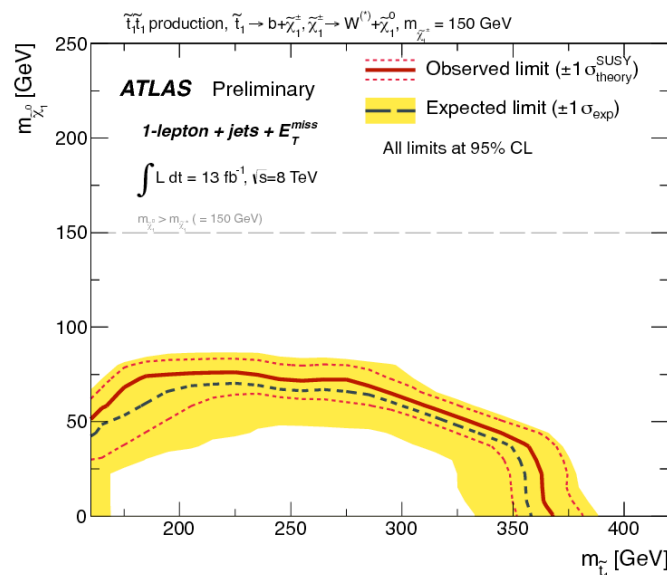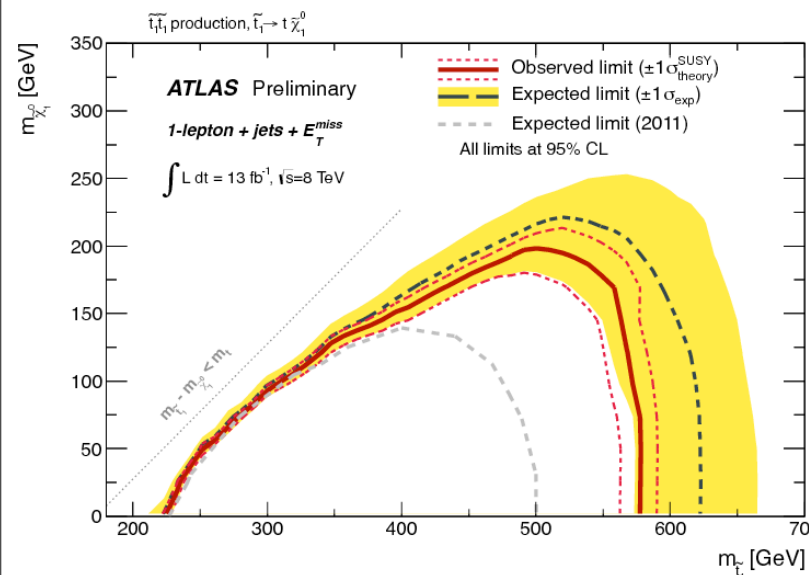
# Signal region definition

## SR1:

- 2 b-jets (130, 50) GeV
- veto 3rd jet (above 50 GeV)
- $m_{CT} > 150, 200, 250, 300$ GeV

## SR2:

- 2 b-jets (60, 60)
- veto 3rd jet (above 50 GeV)
- $E_T^{miss} > 200$ GeV
- $m_{CT} > 100$ GeV
- HT,2 < 50 GeV

## SR3 (a):

- ISR jet 130 GeV, anti b-tagged
- 2 b-jets (30, 30) GeV
- $\Delta\Phi(E_T^{miss}, jet1) > 2.5$
- $p_T$ b-jet 1 < 110 GeV
- HT,3 < 50 GeV

## SR3 (b):

- all SR3(a) cuts
- $E_T^{miss} > 250$
- $p_T$ jet1 > 150 GeV

$$HT,2 = \sum_{jet>2}^{jet\ N} p_T$$

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# Missing transverse energy

- Missing $E_T$ (MET) reconstructed from the vectorial sum of **all final state objects,** each **with a dedicated calibration.**

- Large sensitivity of **missing $E_T$ resolution to pileup** addressed by **usage of tracking information in MET calculation**
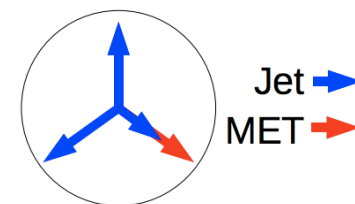
Friday, January 11, 2013
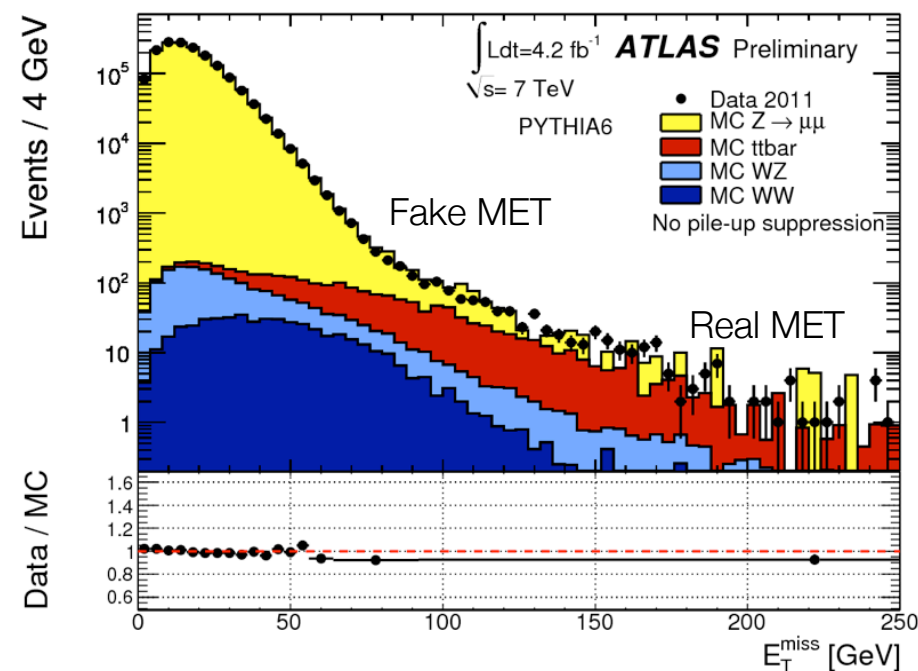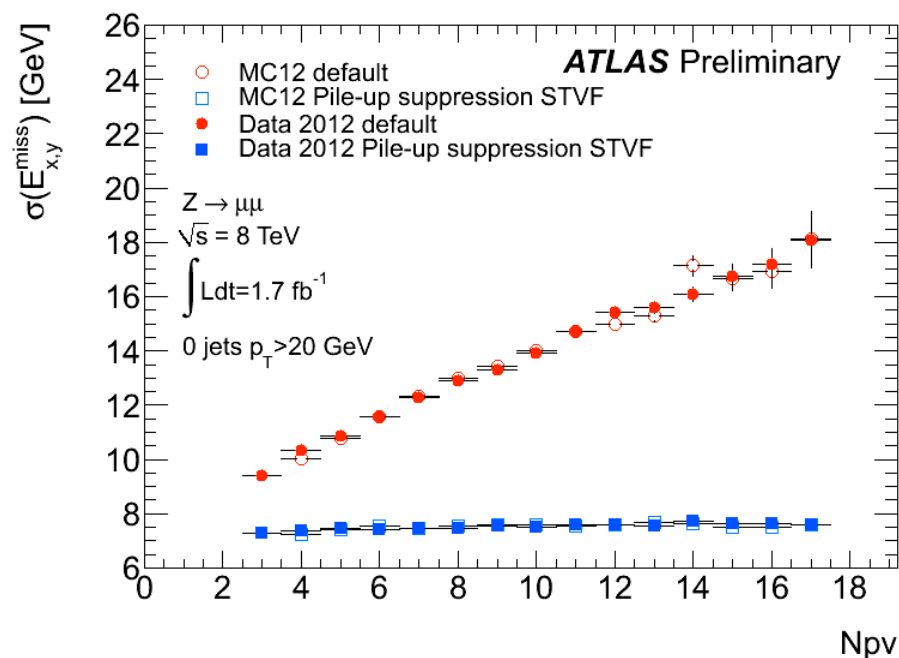
# Fake MET background estimate

- Large MET can be induced by a jet mis-measurement. Relevant for processes with high cross section and no "real" MET (multi-jet, Z→ll)
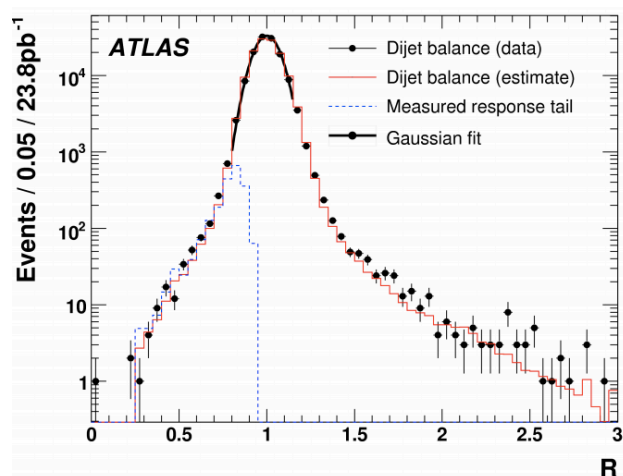
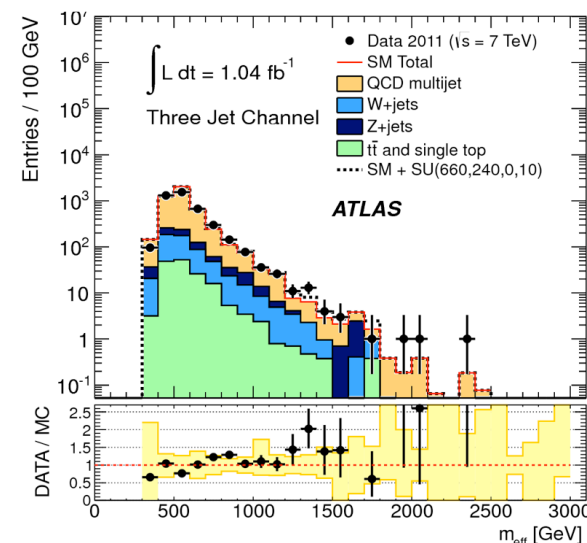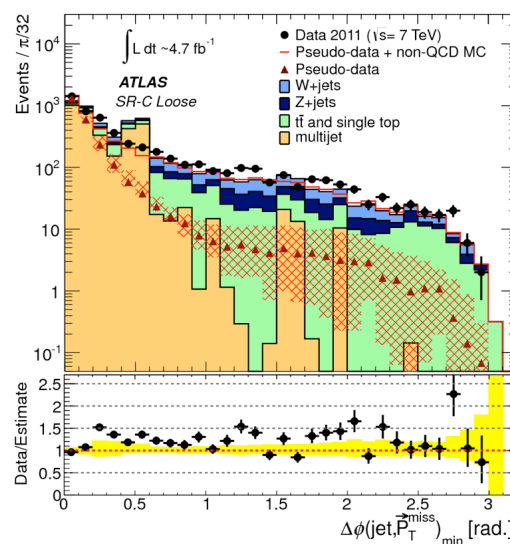

- Derive a "jet response function" from the MC and adapt it to reproduce:

  - $p_T$ balance in di-jet events (core of response function)

  - response tail in three-jet (Mercedes) events



- Use response function to smear real data events with low MET:

  - Obtain events with large "fake" MET

- Validate them in a dedicated control region (MET aligned with one jet)
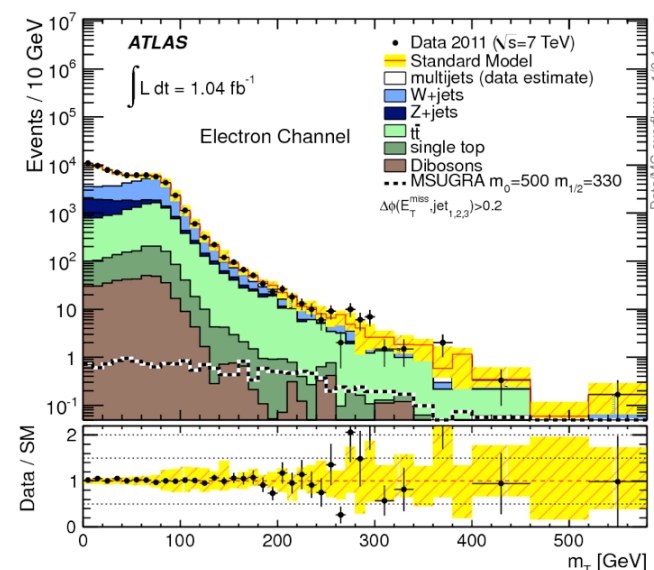
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# Fake lepton background estimate

- General approach to **fake lepton background estimation** based on a loose/tight matrix method

- Example with 1 lepton (easily extendable to multi-lepton signatures): **multijet events can fake 1-lepton signatures if**:

  - a lepton from a **heavy flavour hadron decay** passes the lepton selection

  - electrons from **photon conversions** pass the lepton selection

- Strategy: **define a "loose"** (pre-selected) **and a "tight"** (signal) lepton selection.

- Then, simply solve the following system of equations

$$N^{loose} = N^{loose}_{real} + N^{loose}_{fake}$$
$$N^{tight} = \varepsilon_{real} N^{loose}_{real} + \varepsilon_{fake} N^{loose}_{fake}$$

Need to be measured independently

Simply count how many of them

$$N^{tight}_{fake} = \frac{\varepsilon_{fake}}{\varepsilon_{real} - \varepsilon_{fake}} \left( N^{loose} \varepsilon_{real} - N^{tight} \right)$$



ATLAS

∫ L dt = 1.04 fb⁻¹

Electron Channel

- Data 2011 (√s=7 TeV)
- Standard Model
- multijets (data estimate)
- W+jets
- Z+jets
- t t̄
- single top
- Dibosons
- MSUGRA m₀=500 m₁/₂=330

Δφ(E_T^miss, jet_{1,2,3})>0.2

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# gluino mediated stop production

- Gluinos and stops/sbottoms the only "light" strong interacting particles:

  - gluino mediated stop/sbottom production

  - direct pair production of stops/sbottoms

$$\tilde{g} \qquad t \to jjb$$
$$\tilde{t} \qquad \tilde{\chi}_1^0$$
$$t \to l\nu b$$



$\tilde{g}$-$\tilde{g}$ production, $\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$

$CL_S$ 95% C.L. limits. $\sigma_{theory}^{SUSY}$ not included.

0-lepton, $\geq$ 3 b-jets [$L_{int}$ = 12.8 fb$^{-1}$, 8 TeV] — Expected / Observed
ATLAS-CONF-2012-145

3-leptons, $\geq$ 4 jets [$L_{int}$ = 13.0 fb$^{-1}$, 8 TeV] — Expected / Observed
ATLAS-CONF-2012-151

0-lepton, $\geq$ 6-9 jets [$L_{int}$ = 5.8 fb$^{-1}$, 8 TeV] — Expected / Observed
ATLAS-CONF-2012-103

2-SS-leptons, $\geq$ 4 jets [$L_{int}$ = 5.8 fb$^{-1}$, 8 TeV] — Expected / Observed
ATLAS-CONF-2012-105

$m_{\tilde{\chi}_1^0}$ [GeV] ; $m_{\tilde{g}}$ [GeV]

$\tilde{g} \to t\bar{t}\tilde{\chi}_1^0$ forbidden

**ATLAS** Preliminary

- If gluino pair production dominant (and only stops not too heavy), then the decay is $\tilde{g} \to \tilde{t}t$

- Final state that contains MET (LSP), up to 4 b-jets, up to 12 jets, up to 4 leptons (possibly same sign)

- Three different analyses target this final state:

  - 3-b jets plus MET (up to 6 jets) - ATLAS-CONF-2012-145

  - 2 SS leptons + MET + 4 jets - ATLAS-CONF-2012-105

  - multijet (up to 9 jets) - ATLAS-CONF-2012-103

  - 3-leptons + MET - ATLAS-CONF-2012-151

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# Strong production

- No excess above SM in any of the signal regions:

  - interpreted first as a model-independent 95% C.L. limit on the visible cross section of BSM processes

  - then as an exclusion limit in specific SUSY models

| 1-lepton | Signal region | |
|---|---|---|
| | Electron | Muon |
| Observed events | 10 | 4 |
| Fitted background events | $9.0 \pm 2.8$ | $7.7 \pm 3.2$ |
| Fitted $t\bar{t}$ events | $6.0 \pm 2.2$ | $2.6 \pm 1.9$ |
| Fitted $W/Z$+jets events | $1.5 \pm 0.7$ | $4.2 \pm 2.3$ |
| Fitted other background events | $1.0 \pm 0.7$ | $0.9 \pm 0.3$ |
| Fitted multijet events | $0.4 \pm 0.6$ | $0.0 \pm 0.0$ |
| MC expected SM events | 9.5 | 11.5 |
| MC expected $t\bar{t}$ events | 5.7 | 4.6 |
| MC expected $W/Z$+jets events | 2.4 | 6.0 |
| MC expected other background events | 1.0 | 0.8 |
| Data-driven multijet events | 0.4 | 0.0 |

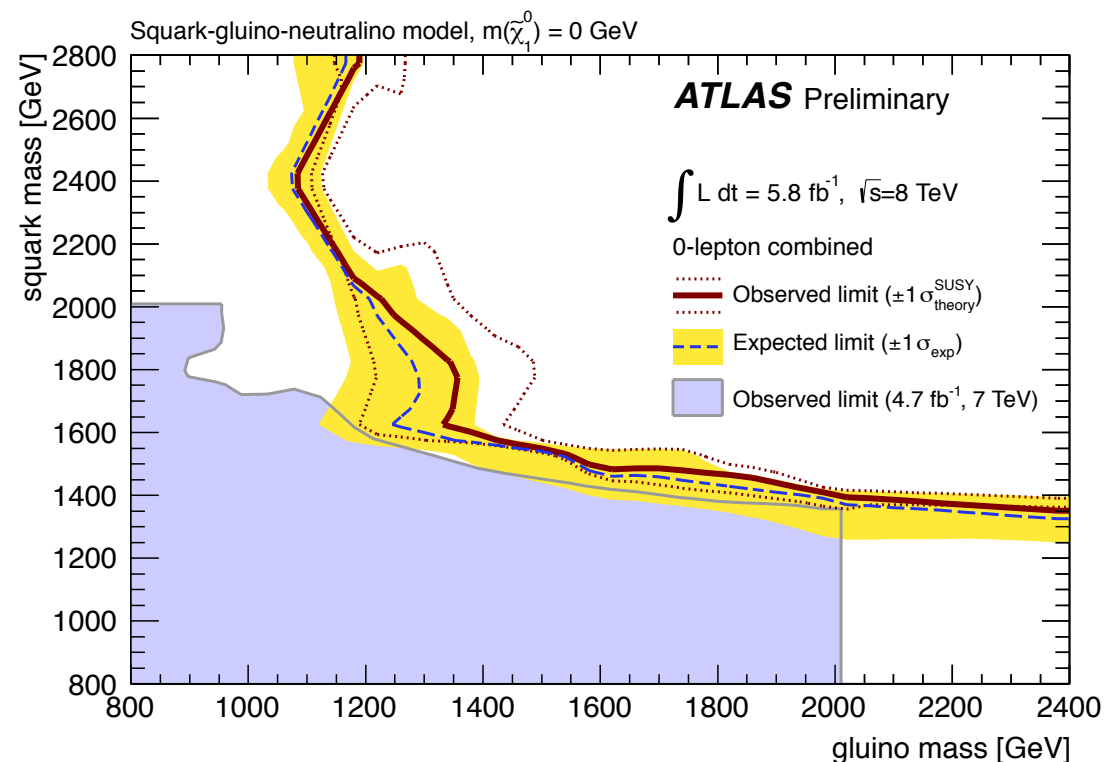| 1-lepton | $\langle\epsilon\sigma\rangle^{95}_{obs}$ [fb] | $S^{95}_{obs}$ | $S^{95}_{exp}$ | $CL_B$ |
|---|---|---|---|---|
| Electron | 1.69 | 9.9 | $9.3^{+3.3}_{-2.6}$ | 0.59 |
| Muon | 1.09 | 6.4 | $8.3^{+3.4}_{-2.3}$ | 0.19 |

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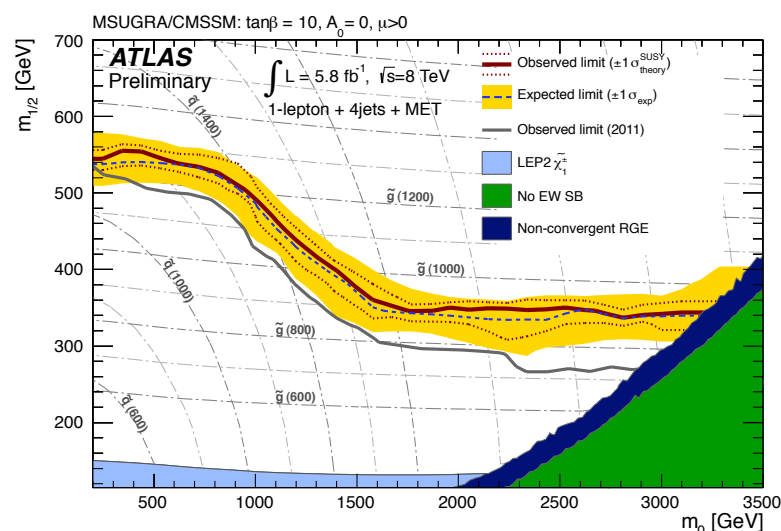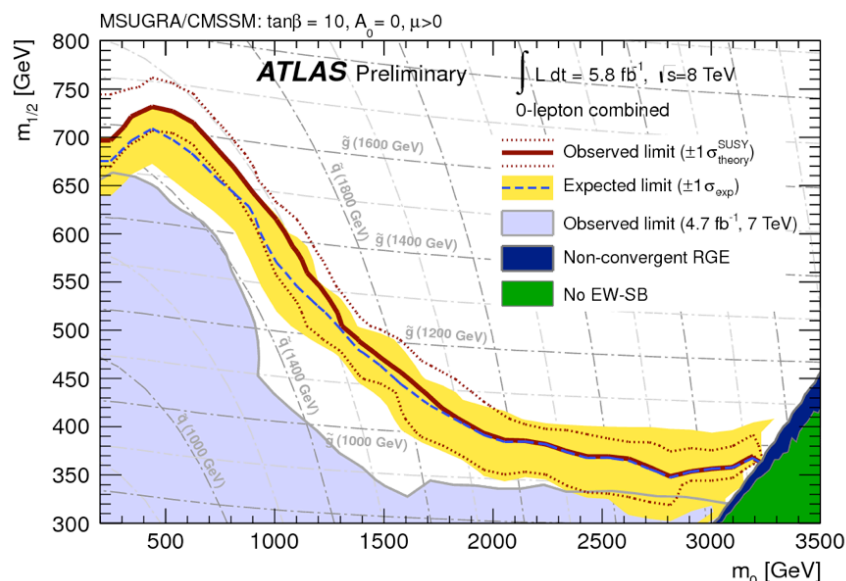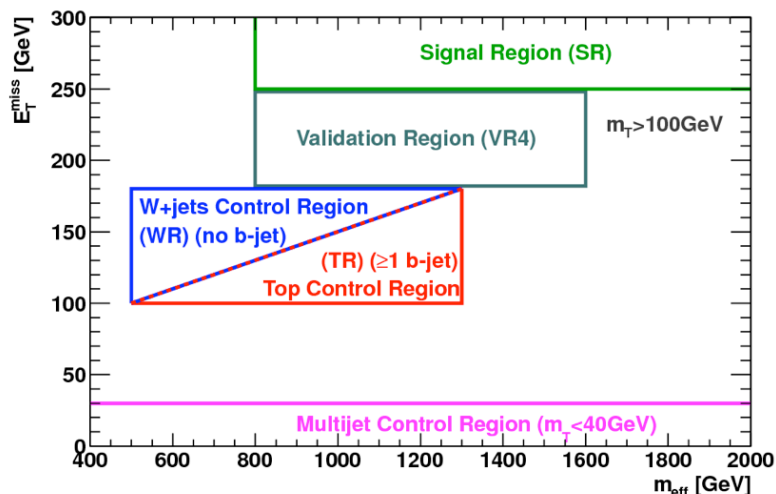
# Strong production

- Simplified models often used in the limit setting

  - Only a few SUSY particles play a role, all others are set to very high masses

- In this case, assume degenerate 1st and 2nd generation squarks. The only possible production processes are

$$\tilde{g}\tilde{g}, \tilde{g}\tilde{q}, \tilde{q}\tilde{q}$$

- only possible processes (depending on masses)

$$\tilde{g} \to qq\tilde{\chi}_1^0, \tilde{g} \to \tilde{q}\tilde{\chi}_1^0, \tilde{q} \to q\tilde{\chi}_1^0$$

- Squark (gluino) masses below 1.3/1.4 (1.1) TeV excluded for any gluino (squark) mass



Squark-gluino-neutralino model, $m(\tilde{\chi}_1^0) = 0$ GeV

**ATLAS** Preliminary

$\int L\, dt = 5.8\ fb^{-1}$, $\sqrt{s}=8$ TeV

0-lepton combined

— Observed limit ($\pm 1\,\sigma_{theory}^{SUSY}$)

- - - Expected limit ($\pm 1\,\sigma_{exp}$)

Observed limit (4.7 fb$^{-1}$, 7 TeV)

squark mass [GeV]

gluino mass [GeV]

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# Strong production



Main SM background processes: top pair production, W production

- Addressed for both analyses with 1-lepton control regions (by selecting the $M_T$ Jacobian peak)

- W and top regions separated by the use of b-tagging

- Z→νν (for 0-lepton) addressed by using a photon + jet control region

- Multijet background addressed using the jet smearing method (0-lepton) or the matrix method (1-lepton)
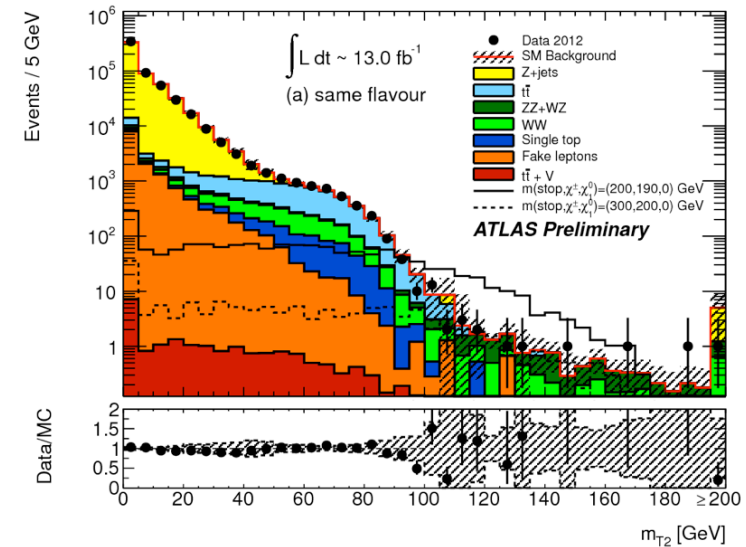


**Z→νν control region**

**top control region**

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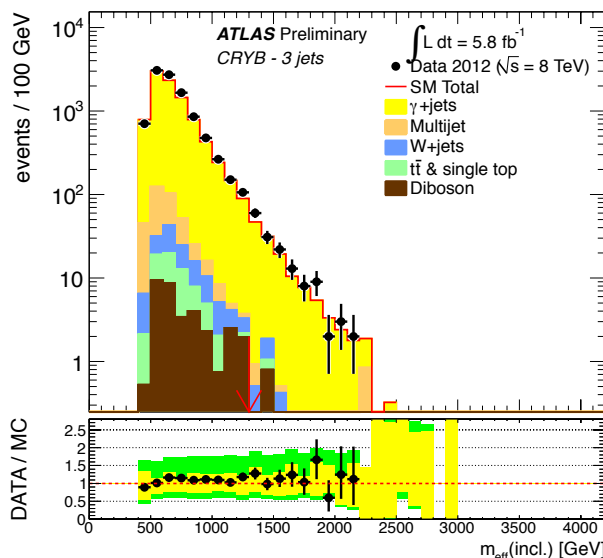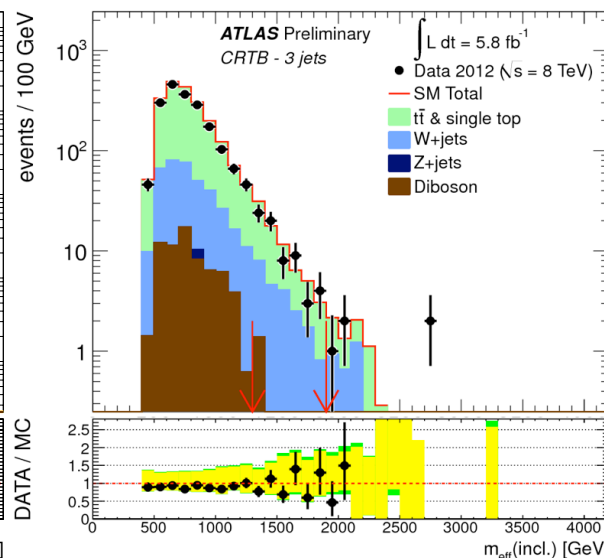
# 2-leptons stop searches

- A dedicated two-lepton analysis addresses best the case $t_1 \to bX_1^\pm$ (BR 100% and $X_1^\pm \to W^\pm X_1^0$) if $\Delta m(t_1, X_1^\pm)$ not too small

- Same and different flavour leptons considered

- Main SM background: tt, WZ

- Basic variable used to reject tt, WW: $M_{T2}$

$$m_{T2}(\mathbf{p}_T^{\ell_1}, \mathbf{p}_T^{\ell_2}, \mathbf{p}_T^{miss}) = \min_{\mathbf{q}_T + \mathbf{r}_T = \mathbf{p}_T^{miss}} \left\{ \max\left[ m_T(\mathbf{p}_T^{\ell_1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{\ell_2}, \mathbf{r}_T) \right] \right\}$$

The exclusion limit concentrated in regions with small $\Delta m(t_1, X_1^\pm)$
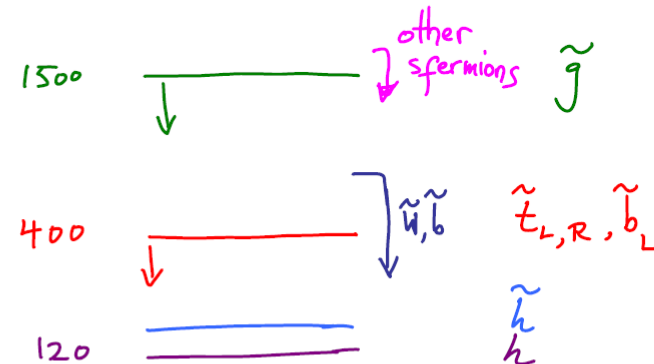
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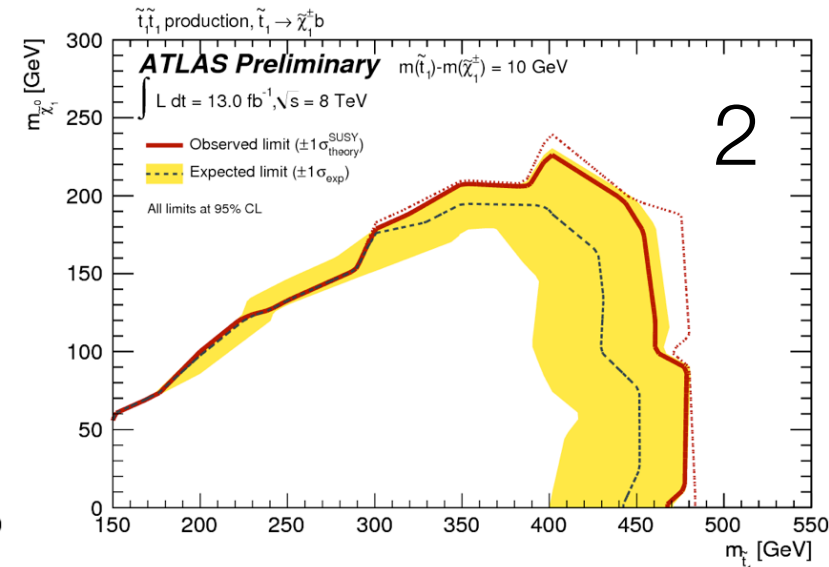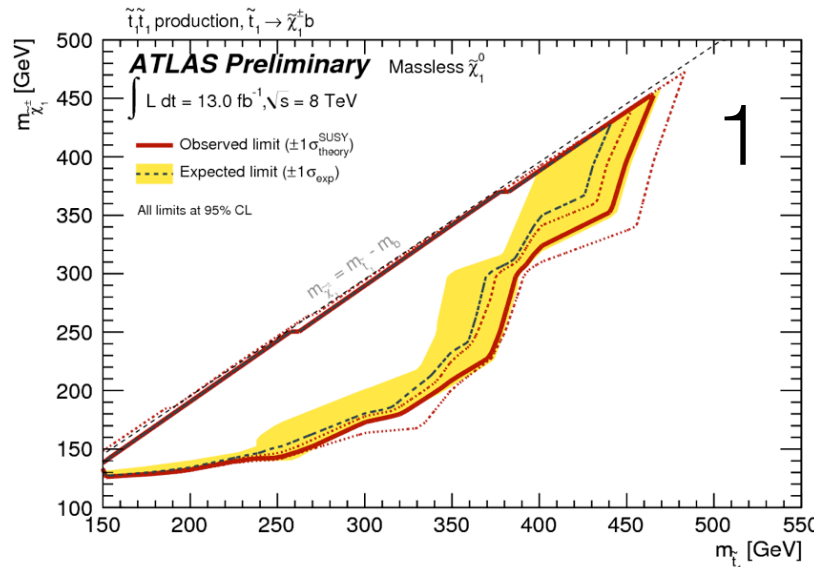
# Is then SUSY dead?

- **No!** (pretty consistent theoretical view on the subject)

- Gluinos and 1st and 2nd generation squarks can be heavy, provided that the superpartners of the heavy fermions are relatively light (still "natural" hierarchy)

- Higgsinos should also be light



A Natural Spectrum

General "bottom-up" viewpoint

L. Hall (LBL Workshop, 21-Oct11)
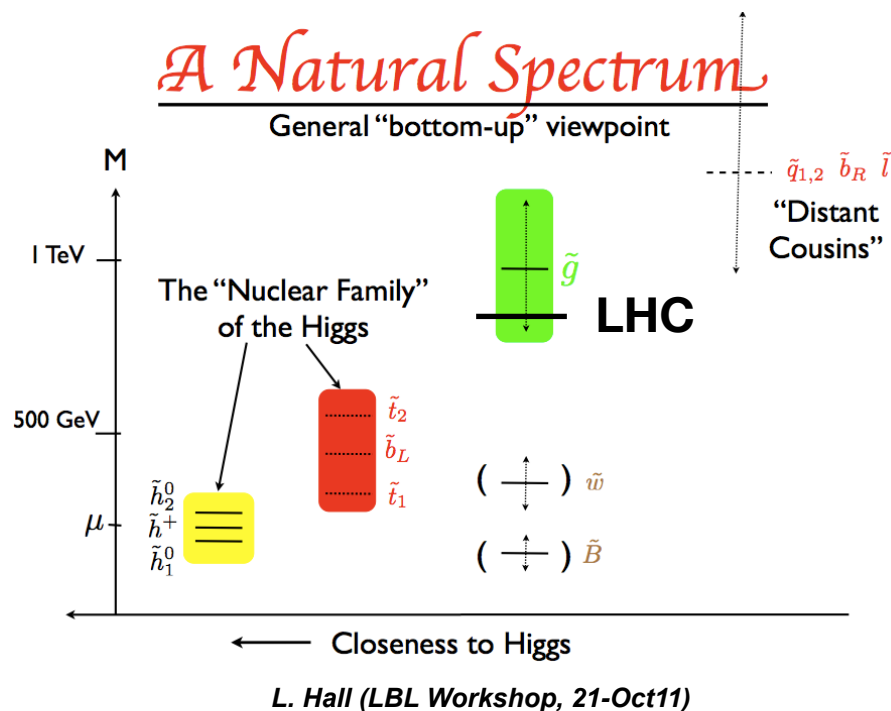
N. Arkani-Ahmed (CERN Workshop, 31-Oct'11)

**... and this is not yet covered by LHC**

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# 3rd generation production

- The third generation squarks are special

- Mixing between L and R component of squarks proportional to the fermion partner mass → large mixing for 3rd generation squarks → generally expected to be the lightest squarks

- Previous limits on squark masses do not apply to sbottom and stop

- The stop directly counter-balance quadratically divergent top loop corrections to the Higgs mass
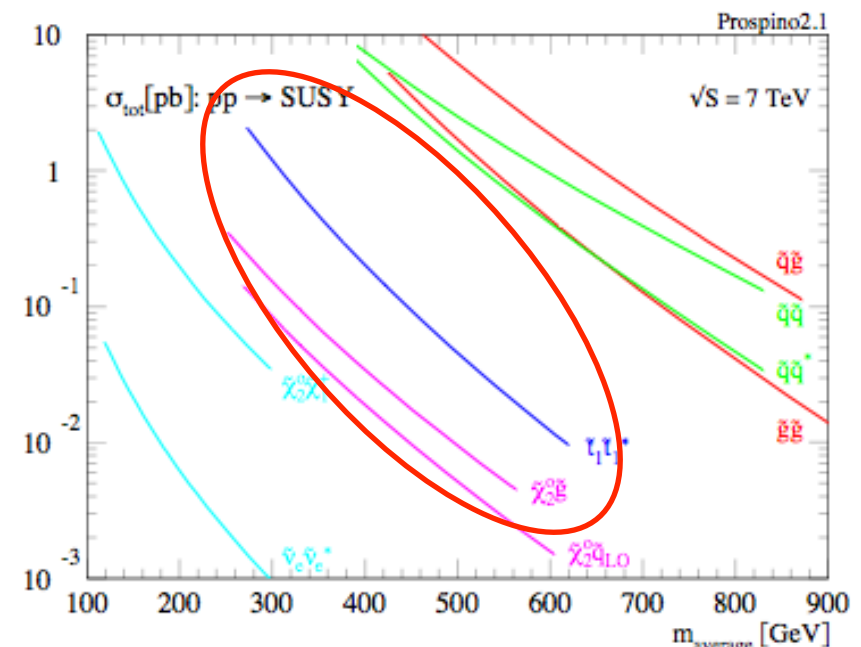
# 0-lepton results

| Signal Region | A-loose | A-medium | B-medium | C-loose | C-medium | E-loose | E-medium |
|---|---|---|---|---|---|---|---|
| | | | MC expected events | | | | |
| Diboson | 53.1 | 18.2 | 11.1 | 6.2 | 0.9 | 0.0 | 0.0 |
| W+jets | 264.1 | 53.5 | 51.9 | 62.9 | 16.4 | 2.1 | 1.9 |
| $Z/\gamma^*$+jets | 338.2 | 74.7 | 50.4 | 55.0 | 16.1 | 1.0 | 0.8 |
| $t\bar{t}$ + single top | 74.9 | 8.1 | 14.2 | 42.6 | 5.3 | 2.1 | 1.6 |
| | | | Fitted background events | | | | |
| Diboson | 53 ± 23 | 18 ± 9 | 11 ± 6 | 6 ± 4 | 0.9 ± 0.6 | – | – |
| Multi-jets | 0.6 ± 0.6 | 0.1 ± 0.1 | 0.2 ± 0.2 | – | – | – | – |
| W+jets | 180 ± 140 | 33 ± 35 | 32 ± 34 | 40 ± 40 | 8 ± 8 | 1.2 ± 1.3 | 0.9 ± 1.1 |
| $Z/\gamma^*$+jets | 354 ± 21 | 81 ± 8 | 59 ± 6 | 67 ± 6 | 18.5 ± 3.0 | 2.0 ± 1.0 | 0.6 ± 0.5 |
| $t\bar{t}$ + single top | 67 ± 16 | 7.6 ± 3.5 | 14 ± 5 | 39 ± 7 | 5.3 ± 2.0 | 2.5 ± 0.9 | 2.0 ± 1.4 |
| Total bkg | 650 ± 130 | 140 ± 33 | 115 ± 30 | 155 ± 31 | 33 ± 8 | 5.7 ± 1.7 | 3.5 ± 1.7 |
| Observed | 643 | 111 | 106 | 156 | 31 | 9 | 7 |
| $p_0$ | 0.498 | 0.500 | 0.500 | 0.486 | 0.498 | 0.161 | 0.108 |
| UL on $N_{BSM}$ | 224.8 | 33.9 | 43.8 | 65.7 | 17.9 | 10.4 | 9.9 |
| UL on $\sigma_{BSM}$ (fb) | 38.8 | 5.84 | 7.55 | 11.3 | 3.09 | 1.79 | 1.71 |

| Signal Region | A-tight | B-tight | C-tight | D-tight | E-tight |
|---|---|---|---|---|---|
| | | MC expected events | | | |
| Diboson | 3.3 | 0.2 | 0.0 | 0.8 | 2.6 |
| W+jets | 6.6 | 5.6 | 2.1 | 3.4 | 3.3 |
| $Z/\gamma^*$+jets | 7.4 | 4.5 | 1.9 | 1.3 | 1.3 |
| $t\bar{t}$ + single top | 1.0 | 1.1 | 0.6 | 1.8 | 2.7 |
| | | Fitted background events | | | |
| Diboson | 3.3 ± 3.1 | 0.2 ± 1.4 | – | 0.8 ± 0.4 | 2.6 ± 2.0 |
| Multi-jets | – | – | – | 0.4 ± 0.5 | 0.1 ± 0.2 |
| W+jets | 3 ± 4 | 2.7 ± 3.4 | 0.3 ± 0.5 | – | 0.8 ± 1.3 |
| $Z/\gamma^*$+jets | 6.8 ± 2.2 | 5.1 ± 1.7 | 2.0 ± 1.1 | 2.5 ± 1.1 | 1.2 ± 0.7 |
| $t\bar{t}$ + single top | 0.8 ± 0.8 | 0.8 ± 0.9 | 0.6 ± 0.5 | 2.6 ± 1.6 | 5.1 ± 3.3 |
| Total bkg | 14 ± 5 | 8.7 ± 3.4 | 2.8 ± 1.2 | 6.3 ± 2.1 | 10 ± 4 |
| Observed | 10 | 7 | 1 | 5 | 9 |
| $p_0$ | 0.499 | 0.500 | 0.499 | 0.500 | 0.499 |
| UL on $N_{BSM}$ | 8.9 | 7.3 | 3.3 | 6.0 | 9.3 |
| UL on $\sigma_{BSM}$ (fb) | 1.53 | 1.26 | 0.57 | 1.03 | 1.60 |

| CR | SR background | CR process | CR selection |
|---|---|---|---|
| CRY | $Z(\to \nu\nu)$+jets | $\gamma$+jets | Isolated photon |
| CRQ | QCD jets | QCD jets | Reversed $\Delta\phi(\text{jet}, \mathbf{E}_T^{\text{miss}})_{\text{min}}$ and $E_T^{\text{miss}}/m_{\text{eff}}(N j)$ cuts |
| CRW | $W(\to \ell\nu)$+jets | $W(\to \ell\nu)$+jets | 30 GeV $< m_T(\ell, E_T^{\text{miss}}) < 100$ GeV, $b$-veto |
| CRT | $t\bar{t}$ and single-$t$ | $t\bar{t} \to bbqq'\ell\nu$ | 30 GeV $< m_T(\ell, E_T^{\text{miss}}) < 100$ GeV, $b$-tag |

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# Minimal SUSY extension of SM (MSSM)

- If SUSY is unbroken, $M_{sparticle} = M_{particle}$. Since sparticles are not yet observed, SUSY must be (softly) broken:

  - $L_{SUSY} = L_{SUSY\ conserving} + L_{SUSY\ soft\ breaking}$

**2 higgs doublets needed → 5 Higgs bosons**

## MSSM parameters:

| SUSY conserving sector | SUSY breaking sector |
|---|---|
| 3 coupling constants for SU(3) xSU(2)sU(1) | 5 3x3 hermitian mass matrices (one per EW multiplet) |
| 4 Yukawa couplings per generation | 3 complex 3x3 matrices (Higgs trilinear couplings to sfermions) |
| | 3 mass terms for the Higgs sector + 2 additional off-diagonal terms |
| | Higgs VEV expectation angle β |

A total of 124 parameters.

**But:** separate lepton number conservation, FCNC suppression, CP violation leave about 20 independent parameters

**Alternatively:** Precise assumptions can be made on the way SUSY is broken:
- mSUGRA/CMSSM
- GMSB
- AMSB

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# (R-parity) conserving SUSY phenomenology

- **Missing** $E_T$ **is the main signature** (although not unique)

- General R-parity signatures:

  - The LSP (typically $\tilde{\chi}_1^0$ or $\tilde{\nu}$ in mSUGRA) is stable and weakly interacting (dark matter candidate) → large missing transverse momentum

  - squarks and gluinos produced in pp collision → large particle multiplicity typically produced in the decay.

- Large jet multiplicities and/or lepton produced in large regions of the parameter space (although not mandatory, e.g. pp→$\tilde{q}\tilde{q}$→qq $\tilde{\chi}_1^0$ $\tilde{\chi}_1^0$)

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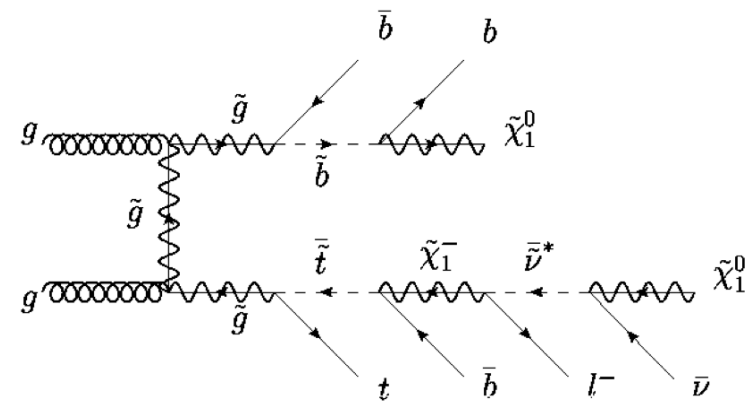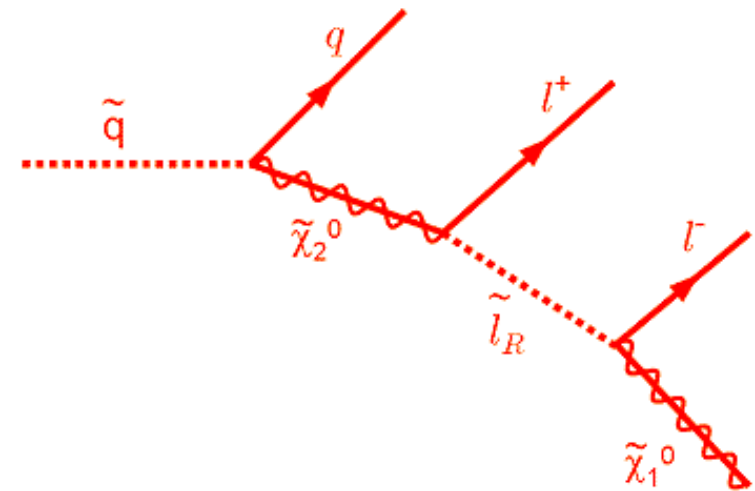
# RPV stop searches

$$W \ni \frac{1}{2}\lambda_{ijk}L_iL_jE_k^c + \lambda'_{ijk}L_iQ_jD_k^c + \frac{1}{2}\lambda''_{ijk}U_i^cD_j^cD_k^c + \mu_iL_iH_u$$

- Depending on which couplings differ from zero, one can get different signatures:

  - Highly ionising tracks (R-hadrons)

  - Two-jet resonances
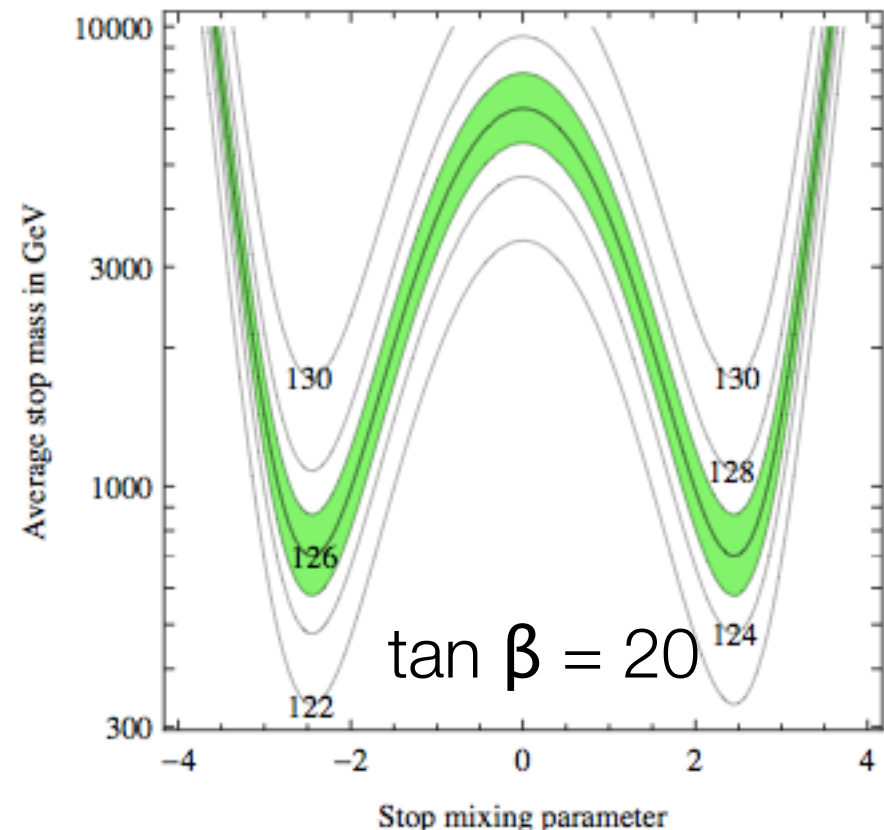
  - Lot of work still to be done here

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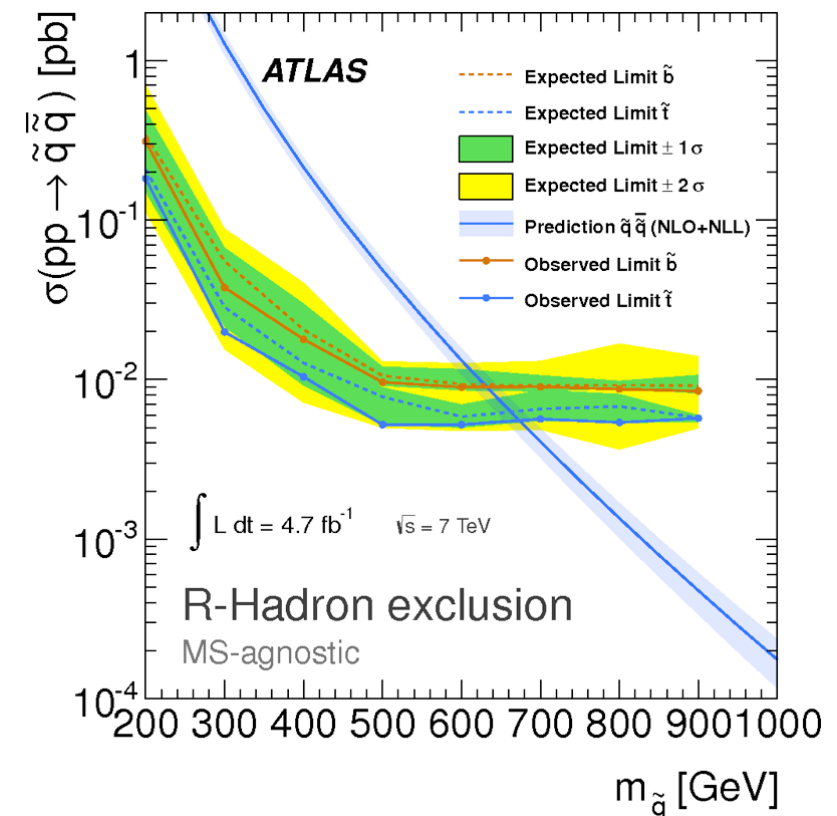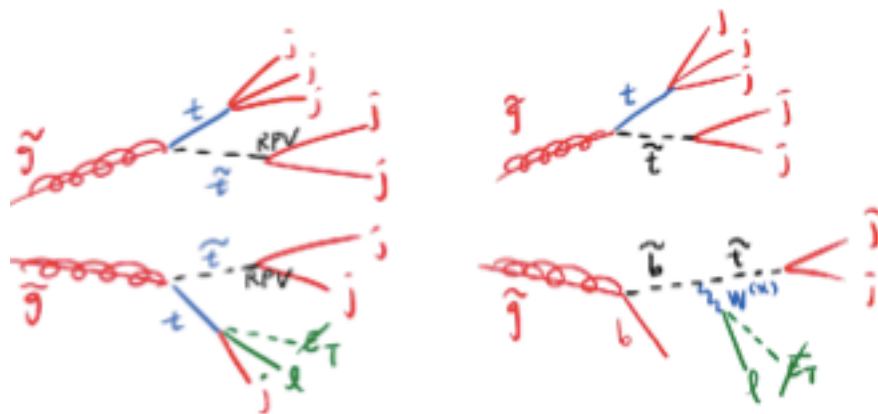
# Higgs and SUSY

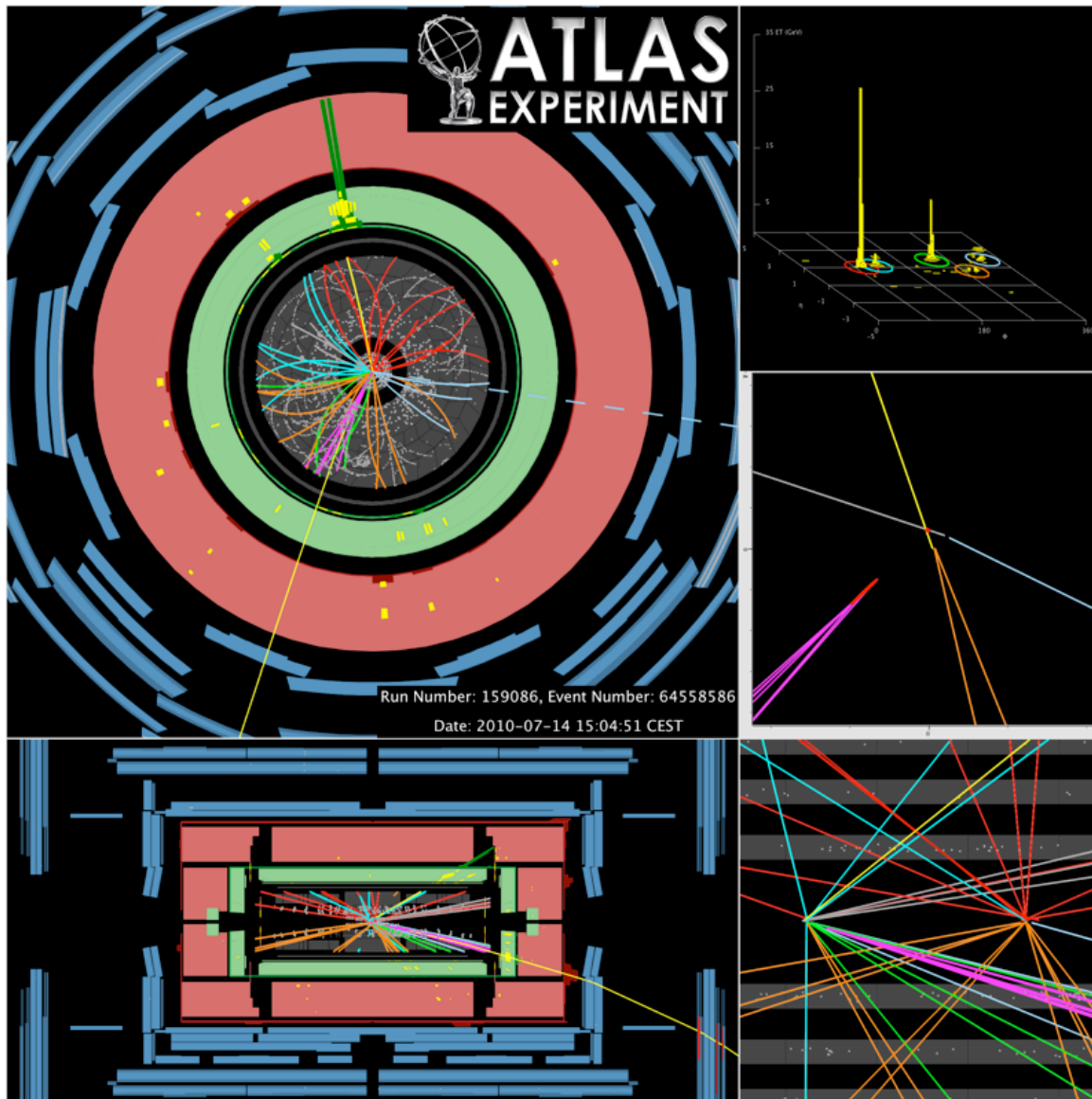$$X_t = (A_t + \mu \cot \beta)/m_S$$

$$m_h^2 = m_Z^2 \cos^2 \beta + \frac{3y_t^2 m_t^2}{(4\pi)^2} \left[ \log \left( \frac{m_S^2}{m_t^2} \right) + X_t^2 \left( 1 - \frac{X_t^2}{12} \right) \right]$$

arXiv:1212.6847

- The Higgs mass depend on the average stop mass and $X_t$

- $m_h$=126 GeV still allows for a light $t_1$



tan β = 20

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# ATLAS in a nutshell (II)



Run Number: 159086, Event Number: 64558586
Date: 2010-07-14 15:04:51 CEST

A dileptonic ttbar event candidate

# An ATLAS event

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